Physikalisch-Technische Bundesanstalt

WGDM-7 Preliminary comparison on nanometrology
According to the rules of CCL key comparisons

NANO 3

LINE SCALE STANDARDS

FINAL REPORT

Braunschweig, August 29, 2003

1 INTRODUCTION

The discussion group for Nanometrology (WGDM7 DG) held at BIPM in June 1998 decided that preliminary comparisons should be held using five different types of artefacts. One set of artefacts chosen were line scale standards. These comparisons are likely to be proposed at a later date as key comparisons. The rules for the organisation of key comparisons should therefore be followed[1]. The pilot laboratory for this ***preliminary comparison*** on line scale standards is the Physikalisch-Technische Bundesanstalt (PTB).

2 STANDARDS

2.1 GENERAL REQUIREMENTS

At the WGDM7 DG meeting, it was proposed to use line scale standards of about 300 mm principal length for the comparison, because this length range is especially important for most challenging manufacturing applications as e.g. in semiconductor industry. Moreover, besides the 300 mm length, the comparison should also cover smaller length ranges down to a few mm only. It was also decided to use two standards of the same design, one made of Zerodur glass ceramic and one made of quartz which both show small thermal expansion coefficients. With this redundant approach it should have been possible to follow any disturbing drift of the line scales and to correct for it. This was important, because the standards had to be newly manufactured for the purpose of this comparison, thus knowledge about the long-term behaviour of the standards was not available at its start.

The standards should meet the requirements of the different line scale measurement methods of the participants. All of the participants used line scale comparators with different types of optical microscopes for line position detection and different laser interferometers for measurement of relative displacement between line scale and microscope. Before the start of the comparison all participants were asked to fill out a questionnaire to describe their measurement instrumentation and based on this information a detailed NANO3 - Technical Protocol was prepared by the pilot laboratory.

2.2 DESCRIPTION OF THE STANDARDS

Because high quality line scale standards were not available, it was decided to have a set of new line scales manufactured. This task was performed by Dr. Johannes Heidenhain company located in Traunreut, Germany in close cooperation with the pilot laboratory[2]. All procurement and manufacturing costs of the standards were accepted by Heidenhain**.**

Two standards of two different materials but with identical layout were circulated within Nano3 comparison. One is made of the glass ceramic Zerodur (#455) and the other of fused silica (#687, quartz, Suprasil II). The dimensions of the scales are 320 mm in length, 20 mm in width and 15 mm in height. The main graduation represents a total length of 280 mm and consists of line structures with 1 mm length and 4 µm width. In addition to

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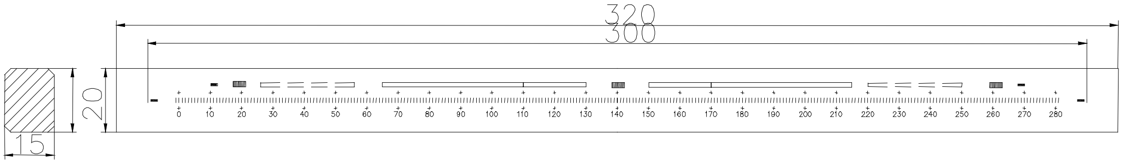
[1] T. J. Quinn, Guidelines for key comparisons carried out by Consultative Committees, March 1, 1999, BIPM, Paris

[2] H. Bosse, W. Häßler-Grohne, J. Tschirnich, J. Flügge, G. Bönsch, P. Speckbacher, W. Israel: Design aspects of the international line scale comparison Nano3, Proc. 2nd Intl. EUSPEN Conf., Torino, 2001, Vol. 1, pp. 302-305

the main graduation a second measuring line with finer pitch and further test structures is located above the main graduation, see Fig. 1. The detailed layout of the scales is given in annex B.

Auxiliary measuring line with test structures:
- Pitch structures with 49 lines each (1 µm, 2 µm, 10 µm, 100 µm pitch)
- CD test structures with CD range from 400 µm down to 0,5 µm



Main graduation: 280 mm length, 1 mm pitch, CD 4 µm, 1 mm line length

Fig. 1: Layout of the Nano3 line scales.

The following measurement tasks were to be performed: On the main graduation deviations from nominal lengths have to calibrated over the total length of 280 mm for every 5 mm graduation line (5 mm pitch) and for every 1 mm line over the first 20 mm of the graduation. On the auxiliary graduation at the pitch structure group in the middle of the scale the deviations from nominal length for the lines of the graduation with 100 µm pitch as well as 10 µm pitch have to be determined by the participants. In all cases, the measurement values have to be referred to reference or "zero" lines. In all cases these were chosen to be the second lines within the graduations in order to use a symmetric environment of neighbouring lines for the datum definition which is particularly important for the fine graduations.

2.3 MANUFACTURING OF THE STANDARDS

The line structures were produced by lithographic techniques in a high reflectivity chromium film with a nominal thickness of 50 nm. The resulting line structures are reflecting on transparent substrates. The surface flatness deviations of the scales are smaller than 0,5 µm, if the scale is supported in the Airy points (distance of x=0,2113·L from both ends => parallel end faces). In order to obtain good long-term dimensional stability of the line scale substrates, suitable raw materials were selected (e.g. old Zerodur raw material produced in 1987 was chosen) and special care was taken during the manufacturing processes (increased temperatures during processing were avoided).

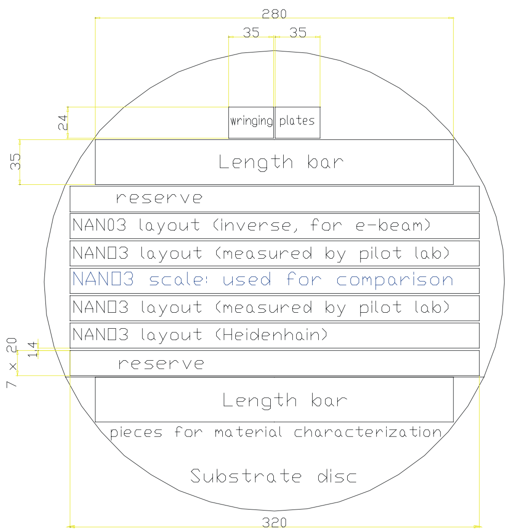


Fig. 2: Substrate disc sectioning of the Nano3 line scales.

In addition to the two circulated standards two control standards and two length bars were produced out of the same raw substrate material discs, see Fig. 2. The control line scales showed the identical design and were treated in the same way as the circulated standards during the manufacturing process, however, some of them were written on purpose with different length scales. All of the control scales were also calibrated by the pilot laboratory and were used to control the long-term drift behaviour of the circulated standards.

A special gauge block interferometer[3]. was employed to determine the thermal expansion coefficients, length compressibility and long-term stability of the length bars substrate materials. It was also carefully tried to expose the gauge blocks to the same temperatures which occurred during line scale processing.

2.4 INVESTIGATION OF SUBSTRATE MATERIAL PROPERTIES

The aforementioned special gauge block interferometer allows to precisely determine length changes upon variation of ambient conditions, namely temperature and pressure. Measurement uncertainties of $2 \cdot 10^{-10}\,K^{-1}$ for thermal expansion coefficients and $0{,}04 \cdot 10^{-10}\,hPa^{-1}$ for length compressibility can be achieved. The measurements of thermal expansion coefficient of the glass ceramic gauge blocks over the temperature range between 10 °C and 30 °C revealed a hysteresis behaviour for the first time. After temperature changes of 10 °C it took the gauge block about a week to relax by about 10 nm to its original length. The results of the substrate material characterizations by gauge block interferometry taking these relaxation effects thoroughly into account can be summarized as:

Zerodur:

- Thermal expansion: $\alpha = [1{,}826 - 0{,}229(t-20)] \cdot 10^{-8}\,K^{-1}$ $U_\alpha = 6 \cdot 10^{-10}\,K^{-1}$
- Length compressibility: $dL_p/L_p = -5{,}76 \cdot 10^{-10}\,hPa^{-1}$ $U_{dLp/Lp}=0{,}08 \cdot 10^{-10}\,hPa^{-1}$

Quartz (Suprasil):

- Thermal expansion: $\alpha = [5{,}386 + 0{,}016(t-20)] \cdot 10^{-7}\,K^{-1}$ $U_\alpha = 3 \cdot 10^{-10}\,K^{-1}$
- Length compressibility: $dL_p/L_p = -9{,}22 \cdot 10^{-10}\,hPa^{-1}$.... $U_{dLp/Lp}=0{,}08 \cdot 10^{-10}\,hPa^{-1}$

Nano3 participants, which evaluate rather small uncertainties of only a few tens of nanometres, should take thermal relaxation as well as length compressibility effects due to variation of ambient pressure into account for analysis of their measurement results.

2.5 INVESTIGATIONS OF LINE SCALE GRADUATION PROPERTIES

Extensive investigations on test line scales as well as the circulated standards were conducted to determine and optimize the line edge quality of the line scale graduations, especially with respect to edge roughness. Because different types of optical microscopes with different characteristics were used by the participants to detect the line edges, special care was taken to obtain line graduations with excellent edge parallelism and edge roughness.

The line edge investigations were all performed by means of the PTB 2D mask comparator LMS 2020[4]. This instrument was also applied as the reference instrument for the line scale

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[3] R. Schödel, G. Bönsch: Interferometric measurements of thermal expansion, length stability and compressibility of glass ceramics, Proc. 3rd Intl. EUSPEN Conf., Eindhoven, 2002, Vol. 2, pp. 691-694

[4] Röth, K.-D., Bläsing-Bangert, C.: Actual Performance Data On The New Pattern Placement Metrology Tool Leitz LMS 2020. Microcircuit Engineering, 1993.

calibrations of the pilot laboratory. It uses a special scanning slit confocal microscope for the line edge detection, which can also be applied to investigate edge roughness properties.

Fig. 3 and Fig. 4 show some typical measurement results of the line scale edge quality.

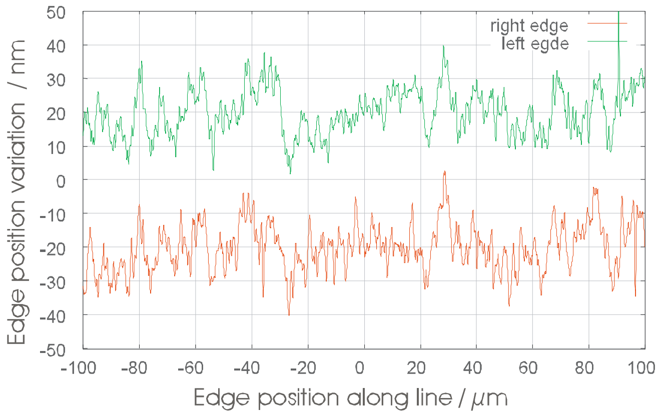

Fig. 3: Line edge position deviation measured along one line of the main graduation over a 200 µm section by means of parallel beam scanning.

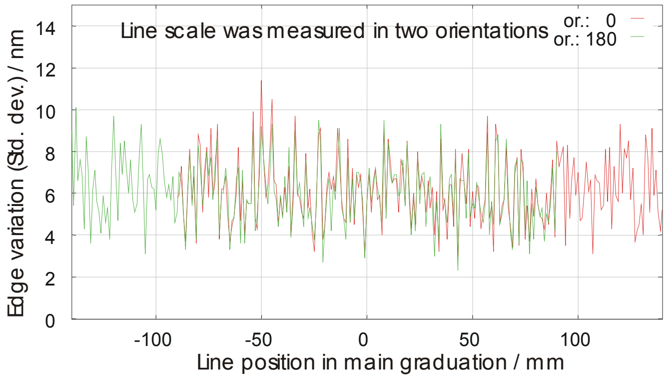

Fig. 4: Line edge position variation measured on all lines of the main graduation over 100 µm sections by means of 9 consecutive measurement scanning slits each 12,5 µm in width (beam scanning orthogonal to line edge).

The mean line edge roughness measured on the main graduations of the circulated line scale standards was determined to be about 7 nm rms (2σ).

3 Participants and Time schedule

3.1 Organisation

Following the rules for key comparison set up by the BIPM[5] a small group of participating laboratories has drafted a technical protocol for the comparison. The group is composed of the pilot laboratory and two participating members (METAS, NRC; PTB: pilot). By their declared intention to participate in this comparison, the participants accepted the general instructions and the technical protocols specified in the ***NANO3 - Technical Protocol*** document and committed themselves to follow the procedures strictly.

3.2 Requirements for participation

According to the WGDM recommendation No.2 (document CCDM/WGDM/97-50b), the participating laboratories should offer this measurement as a calibration service (now or in

[5] see http://www.bipm.org/pdf/guidelines.pdf

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 was set to a standard uncertainty of approximately 75 nm for the principal length of 280 mm. Most of the participants did offer calibrations with substantially smaller measurement uncertainties already at the preparation of the comparison. In addition instrument improvements were under way in several institutes which would most probably allow further reduction of measurement uncertainty on high quality line scales in the course of the comparison.

3.3 PARTICIPANTS IN THE CIRCULATION

The participants of the Nano3 comparison are listed in Table 1.

Table 1: Participating laboratories

Contact Person	**National Metrology Institute**	Contact details
William Penzes	**NIST**, National Institute of Standards and Technology, Nano-Scale Metrology Group Gaithersburg, MD 20899-0001, **USA**	Tel. +1 301 975 3477 Fax +1 301 869 0822 e-mail: William.Penzes@nist.gov
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Marco Pisani Gian Bartolo Picotto	**IMGC** Strada delle Cacce 73 10135 Torino **ITALY**	Tel.: +39 11 39 771 *Fax: +39 11 39 77 459* e-mail: G.Picotto@imgc.cnr.it M.Pisani@imgc.to.cnr.it
Georges Vailleau	**BNM/LNE**, Laboratoire National d´Essais Division 320, Métrologie dimensionnelle Rue Gaston Boissier 1 F-75724 Paris, Cedex 15, **FRANCE**	Tel.: +33 1 40 43 38 24 Fax: +33 1 40 43 37 37 e-mail: Georges.Vailleau@lne.fr
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Together 13 participants have measured the circulated line scale standards, however two participants (NRC and KRISS, marked grey in Table 1) decided to officially withdraw their participation after their measurements were performed, because they encountered problems during the analysis of their measurement data.

3.4 TRANSPORTATION OF THE STANDARDS

For circulation of the sensitive standards a special transportation device was prepared. This device consists of two suitcases, see Fig. 5. The outer suitcase was designed to provide a coarse protection during international transportation. The inner suitcase contained the line scale boxes which were supported in specially selected damping foam material. Within the inner suitcase, additional sensors were mounted for continuous monitoring of ambient conditions during transport (temperature, humidity and shock sensors). Each line scale box contained one transfer standard which was protected from dust within a transparent, plastic housing, see Fig. 6. The transparent housing was to be opened under clean ambient conditions only and handling of the scales was to be performed always wearing appropriate gloves, which were provided within the suitcase. Following these instructions, cleaning of the standards was thought to be avoidable during circulation.

Fig. 5: Nano3 transportation package.

Fig. 6: Line scale box with Zerodur scale.

3.5 TIME SCHEDULE

The comparison started in April 2000 and was originally scheduled to be finished in the end of 2001, see Annex A. It was organized in a mixed form, circulation and star type. The period of time available for each laboratory was 5 weeks for calibration including transportation to the next participant.

Reasons for the overall delay of the comparison were manifold. As the standards sometimes were severely contaminated during the circulation some additional cleaning procedures had to be performed by the pilot laboratory, see e.g. Fig. 7. Moreover, the pilot laboratory also tried whenever possible to re-calibrate the standards in between the circulations.

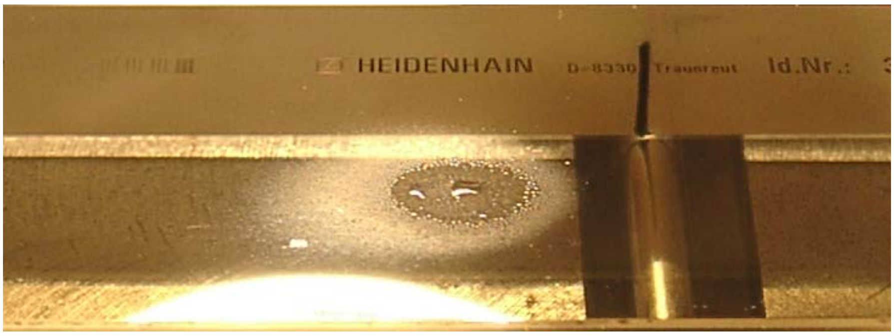

Fig. 7: Example of severe contamination of circulated standard.

An ATA CARNET was mostly used for transportation of the standards. However, sometimes the ATA CARNET seemed to be the reason for severe delays of customs clearance. This was definitely the case e.g. for transportation to and from Russia. In between the circulation also the order of measurements had to be changed due to these difficulties. After the circulation a larger delay was caused by the pilot laboratory because it intended to also include first measurements results on the Nano3 scales by means of its new vacuum line scale comparator, which could be performed in the beginning of 2003 at the earliest.

***Table 2: Circulation of standards** (organized in 3 loops)*

Delivering Lab	Receiving Lab.	Delivery of standards	Reception of standards	Delivery of results	Transport conditions: Carnet ,T_{min}/T_{max}, RH_{min}/RH_{max}
PTB	**NIST**	2000-05-09	2000-06-01	2001-03-31	C, 16/26, 35/41
NIST	**NRC**	2000-07-07	2000-07-17	withdrew partic. on 2001-11-30	C, 23/27, 43/46
NRC	PTB	2000-08-18	2000-08-29	-	C, 18/47, 34/54
PTB	**METAS**	2000-09-05	2000-09-06	2000-12-08	C, 14/23, 44/46
METAS	PTB	2000-09-21	2000-09-26	-	C, 13/22, 46/50
PTB	**CMS/ITRI**	2000-09-26	2000-10-03	2001-03-16 *(2003-04-02)**	-, 14/32, 45/50
CMS/ITRI	**NIM**	2000-11-08	2000-11-20	2001-05-14	-, 5/25, 39/48
NIM	PTB	2000-12-13	2000-12-22	-	-, -1/22, 17/33
PTB	**NMIJ**	2001-01-03	2001-01-09	asked for re-measurement on 2001-01-27	C, 5/21, 36/40
NMIJ	**KRISS**	2001-01-29	2001-02-08	withdrew partic. on 2002-01-17	C, 3/18, 41/50
KRISS	PTB	2001-03-10	2001-03-18	-	C, -3/23, 24/44

PTB	**MIKES**	2001-05-02	2001-05-04	2001-06-18	-, 16/25, 40/44
MIKES	**SP**	2001-06-07	2001-06-11	2001-09-12	-, 10/24, 44/51
SP	PTB	2001-07-11	2001-07-12	-	-, 17/22, 55/58
PTB	**VNIIM**	2001-07-16	2001-07-26	Customs problem VNIIM could not receive standards	C, 17/30, 47/55
VNIIM	PTB	2001-09-13	2001-09-26	-	C, 11/21, 53/60
PTB	**IMGC**	2001-10-24	2001-10-26	2002-10-04 *(2003-04-07)**	-, 13/20, 44/47
IMGC	PTB	2001-11-30	2001-12-03	-	-, 12/23, 44/49
PTB	**VNIIM**	2001-12-06	2001-12-17	2002-03-04 *(2003-04-07)**	-, -12/21, 44/60
VNIIM	**NMIJ**	2002-01-31	2002-02-08	2002-09-05 *(2003-04-01)**	-, -10/21, 21/40
NMIJ	**LNE**	2002-03-08	2002-03-11	2002-06-24	-, 9/22, 43/50
LNE	PTB	2002-04-25	2002-04-29	-	

The maximum and minimum temperatures and relative humidities monitored during transportation are given in the right column of Table 2, extreme values are marked in red. In between the circulation the standards were all stored at PTB under temperature controlled clean room conditions (20 °C, RH 45% ± 5%). As can be seen in Table 2, two participants decided to officially withdraw their participation in Nano3 after the measurements were carried out. NMIJ observed malfunctions of their laser interferometer during the first measurements and therefore asked for the possibility to re-measure at a later date. Only one participant was able to provide the measurement report within the usual time frame of six weeks after the measurements were performed.

*) After analysis of the results, the pilot laboratory asked four participants in March 2003 to carefully re-check their measurement data, because inconsistencies were found with respect to the results of all participants (E_N-values > 1). The four participants responded with revised measurement data or uncertainty budgets on the dates denoted in brackets.

4 MEASURANDS

The different measurands to be determined on the two circulated standards are the deviations from the nominal lengths or positions:

1) <u>On the main graduation:</u>

All measurement values were to be referred to the reference line at position "0"[6]

A) Deviation from nominal length between first and last graduation line (280 mm)
B) Deviations from nominal length for every 5 mm graduation line (5 mm pitch)[7]
C) Deviations from nominal length for 1 mm lines, but only within the first 20 mm of the main graduation

2) <u>On the auxiliary graduation, at the pitch structure group in the middle of the scale:</u>

All values were to be referred to the second line (left side) in each pitch structure group

D) Deviations from nominal length for 47 lines of the graduation with 100 µm pitch over the length of 4.6 mm (deviations of 46 lines with respect to the second line).
E) Deviations from nominal length for 47 lines of the graduation with 10 µm pitch over the length of 0.46 mm.

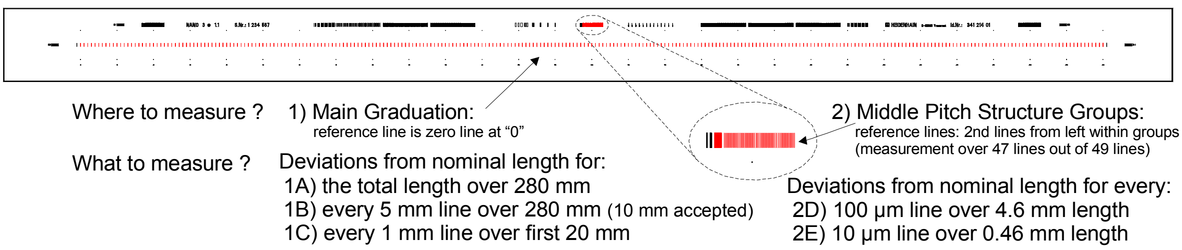

Fig. 8: Definition of measurands used in the Nano3 comparison.

The most important measurands are those on the main graduation. Especially measurement task 1B, because here different length scale realizations of the participants should be revealed. The measurements tasks over smaller lengths (1C, 2D and 2E) on the other hand should also provide supporting information about differences in line edge detection.

Not all participants were able to perform the measurements on the auxiliary graduations, but all of them provided data for the measurands on the main graduation. For each measurement result, a detailed estimation of the measurement uncertainty according to the ISO ***Guide to the Expression of Uncertainty in Measurement (GUM)*** had to be provided. All measurement results had to be referred to reference conditions with the coefficients provided by the pilot laboratory (temperature: 20 °C; ambient pressure: 1013.25 hPa).

[6] Please note: there are also lines at positions "-1" and "281" for symmetry reasons.
[7] 5 mm pitch was the **default** condition. However, 10 mm may also be used in case of inacceptable overall measurement times (e.g. on older comparators), which would otherwise enlarge uncertainties.

5 Measurement Methods

The participants were asked to choose their usual method of measurement for line scale calibrations. Only the support of the line scales at the Airy points and the measurement window length along the line section of 100 µm was prescribed. With the exception of the PTB all other participants used one method of measurement only, however, also the PTB used only one instrument (LMS 2020) for the official calibrations within Nano3. Table 3 gives an overview of the methods applied. The full description of the measurement methods and instruments by the participants can be found in appendix C.

Table 3: Overview of instrumentation used for measurements

Institute	**Instrument description (short overview):** Translation, Refractometry, Microscope, Edge	**Meas. Range**	**Meas. Uncertainty, U_{95}:** Nano3 / CMC entry $Q[a,b] = [a^2+b^2]^{1/2}$ U_{95} in nm with L in mm
NIST	Moving scale on carriage with roller bearing, static mode Edlen parameter method for n-correction Photoelectric microscope, scanning slit, 100x edge criterion: 50% intensity	1 m	Nano3: Q[6, 0.12L] CMC-Entry: -
NRC	Moving scale on carriage on air bearing, static Edlen parameter method for n-correction CCD microscope, NA=0.2 edge criterion: ?	0.8 m	Nano3: withdrawn expected: Q[50, 0.2L] CMC-Entry: -
METAS	Moving scale on x-y-stage on air bearing, static mode Edlen parameter method for *n*-correction CCD microscope, NA=0.46, 20x and 0.9, 50x moment based edge detection operator	0.4 m	Nano3: Q[20, 0.082L] CMC-Entry: Q[20, 0.1L]]
CMS/ITRI	Moving scale on carriage with roller bearing, static mode Edlen parameter method for n-correction CCD microscope, scanning slit, NA=0.8, 50x edge criterion: evaluated over 2/3 of edge trans.	1 m	Nano3: Q[161, 0.12L] CMC-Entry: -
NIM	Moving scale on carriage with slide bearing, dynamic mode @ 1,3 mm/s Edlen parameter method for *n*-correction Photoelectric microscope, dual slit type, NA=0.2, 80x, transmission mode edge criterion: equal intensity of both slits	1 m	Nano3: Q[103, 0.09L] CMC-Entry: Q[500, 0.5L]
NMIJ	Moving scale on carriage with air bearing, dynamic mode @ 0.5 mm/s Ciddor parameter method for *n*-correction Photoelectric slit microscope, NA=0.55, 50x edge: halfway in x between 25% and 75% int.	1 m	Nano3: Q[41, 0.32L] CMC-Entry: Q[150, 0.25L]
KRISS	Moving microscope on carriage, dynamic mode Edlen parameter method for *n*-correction Photoelectric slit microscope, NA=0.4, 32x, edge criterion: ?	2 m	Nano3: withdrawn expected: Q[20, 0.2L] CMC-Entry: -
MIKES	Moving microscope on carriage, dynamic mode @ 0,2 mm/s Edlen parameter method for *n*-correction CCD microscope, 25x and 10x	1 m	Nano3: Q[18, 0.084L] CMC-Entry: Q[50, 0.14L]

	mean of interpolated values between 45%-75%		
SP	Moving microscope on carriage with roller bearing, static Edlen parameter method for *n*-correction Photoelectric microscope, slit type, 5x Intensity level edge definition: ?	3 m	Nano3: Q[242, 0.74L] CMC-Entry: Q[500, 0.5L]
VNIIM	Moving microscope on carriage with Teflon bearing, dynamic mode @ 0,05 mms Refractometer chamber of 1 m length Photoelectric confocal microscope, scanning slit type, NA=0.9 centroid of line sections between 25%-40%	1 m	Nano3: Q[7, 0.1L] CMC-Entry: Q[20, 0.3L]
IMGC	Moving scale on carriage with slide bearing, Moore No. 3 CMM, static mode Edlen parameter method for *n*-correction CCD microscope, NA=0.8, 125x intensity thresholds for left/right edge detection	0.5	Nano3: Q[81, 0.13L] CMC-Entry: -
LNE	Moving microscope on carriage on air bearing, dynamic mode @ 5µm/s Edlen parameter method for *n*-correction Photoelectric slit microscope, 10x edge criterion: centre of line	3 m	Nano3: Q[62, 0.12L] CMC-Entry: Q[50, 0.8L]
PTB 1: **LMS** 2020: 2D mask comparator	Moving stage on air bearing, static Tracking refractometer, parameter initialization Scanning slit confocal microsc., NA=0.9, 100x 50% line edge position from fit over 20%-80%	0.3 m	Nano3: Q[9, 0.13L] CMC-Entry: Q[10, 0.15L]
PTB 2: **nmK**: Nanometer Comparator	Moving scale carriage on air bearing, dynamic mode @ 1 mm/s, iodine stabilized green Nd:YAG vacuum laser interferometer Photoelectric microscope, slit type, NA=0,55, 50x , 50% line edge position from fit over 35%-80% *Instrument is not yet fully operational*	0.6 m	Preliminary estimation: Q[41, 0.015L] Target: Q[4, 0.003L]
PTB 3: **AIK**: Automatic Interference Comparator	Moving scale carriage on Teflon bearing, dynamic mode @ 1 mm/s HeNe laser interferometer, Refractometer Photoelectric slit microscope, NA=0,17 Interpolation between closest 2 values below and above 50%, *Instrument dismantled in 2000*	1.2 m	old CMC-Entry: Q[20, 0.055L]

6 Stability of the Standards

Standards used for comparison purposes should be stable in order to allow a meaningful analysis of the results of the participants during the time needed for circulation. For this comparison, however, no suitable standards with known metrological history were available and it was thus decided to have new standards manufactured.

As already stated, special care was taken to select suitable substrate raw material and process conditions to achieve standards with sufficient stability. Moreover, two different substrate materials were chosen for the circulated standards and some control line scales were manufactured out of the same raw materials, which should allow to monitor possible drift influences of the newly manufactured scales.

It is well known e.g. that the glass ceramic material *Zerodur* exhibits a long-term relaxation behaviour which results in a continuous length reduction. The manufacturer specifies the length changes of offered Zerodur material to be smaller than 10^{-7}/a. According to long-term investigations of the length stability of Zerodur gauge blocks[8] the annual contraction rate was found to be about $3{\cdot}10^{-8}$/a for material being 10 years old (newly frozen Zerodur material contracts at rates of about $6{\cdot}10^{-7}$/a). As the chosen Zerodur substrate material for this comparison was produced in 1987 and the Nano3 line scales were manufactured from this material in 1999, the expected length changes of the scales were estimated to be smaller than $3{\cdot}10^{-8}$/a and thus acceptable for the comparison.

Another important aspect for the appropriateness of the circulated standards for the comparison is the line structure quality, especially a constant degree of good cleanliness of the measurement structures throughout the circulation. Due to the star-type schedule of the comparison, the pilot laboratory could carefully re-clean the line standards in between, which sometimes were severely contaminated. Also, every participant was asked to perform an inspection of the incoming circulated standards. Some participants reported contamination effects, however the pilot laboratory judged these disturbances not to be decisive for the comparison.

Calibrations of the two circulated standards by the pilot laboratory were primarily performed with the LMS 2020 2D mask comparator. This was the only PTB instrument which was available and in operation during the whole comparison and therefore serves as the reference instrument of the pilot laboratory. However, in the beginning and in the end of the comparison two other PTB line scale comparators (AIK[9], nmK[10], see Table 3) were also used for independent measurements on the objects.

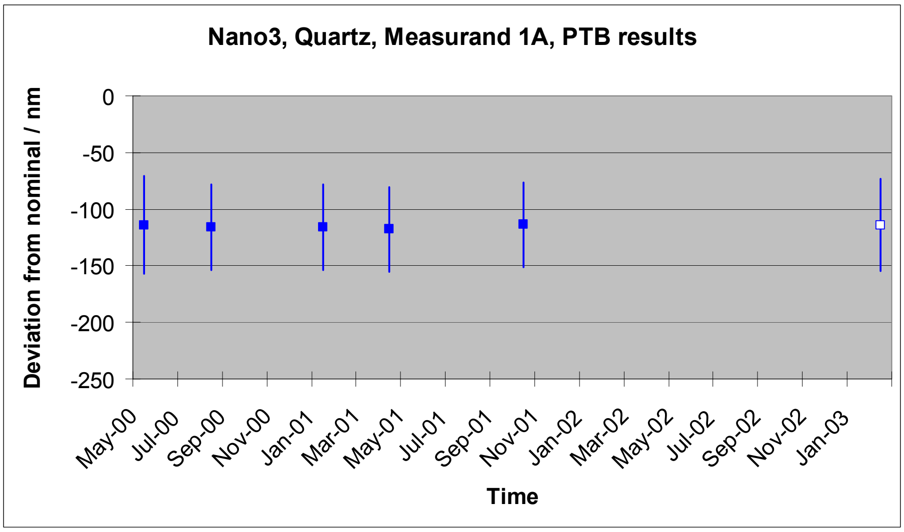

Fig. 9: Results of successive calibrations of the pilot laboratory on the quartz line scale: deviations from nominal value of 280 mm principal length, Measurand 1A (open symbol: nmK result, full symbol: LMS 2020).

[8] F. Bayer-Helms, H. Darnedde, G. Exner: Längenstabilität bei Raumtemperatur von Proben der Glaskeramik “Zerodur”, 1985, Metrologia, 21, pp. 49-57
[9] H. Pieles et al: Vergleichsmessung an Strichmaßstäben, PTB-Mitteilungen, 101, 6, 1991, 403-407
[10] J. Flügge, R. Köning: Status of the nanometer comparator at PTB, *Proc. SPIE 4401*, pp. 275-283, 2001

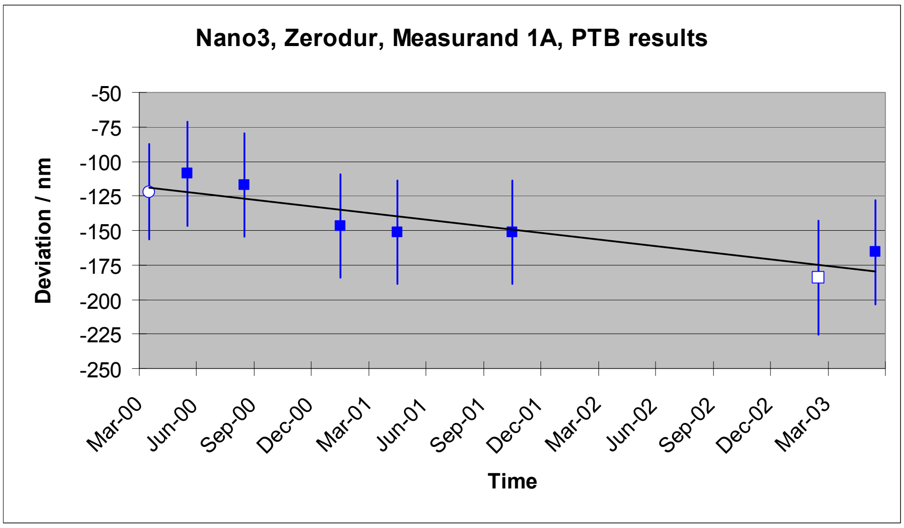

Fig. 10: Results of successive calibrations of the pilot laboratory on the Zerodur line scale: deviations from nominal value of 280 mm principal length, Measurand 1A (open square symbol: nmK result, open circle: AIK result, full symbol: LMS 2020).

Both scales were about 100 nm shorter than the nominal length of 280 mm. Whereas the quartz scale showed excellent stability, the length of the Zerodur scale tends to decrease over the time of the circulation with an annual rate of about 19 nm/year (linear approximation). To take this length change of the standard into account for the analysis of the comparison, a compensating **drift correction** had to be applied to all of the participants' results on the Zerodur scale, see section 6.2.

The re-calibrations also clearly revealed, that only the total length of the graduation changed, while the position deviations of the line structures, i.e. its characteristic signature, remained constant.

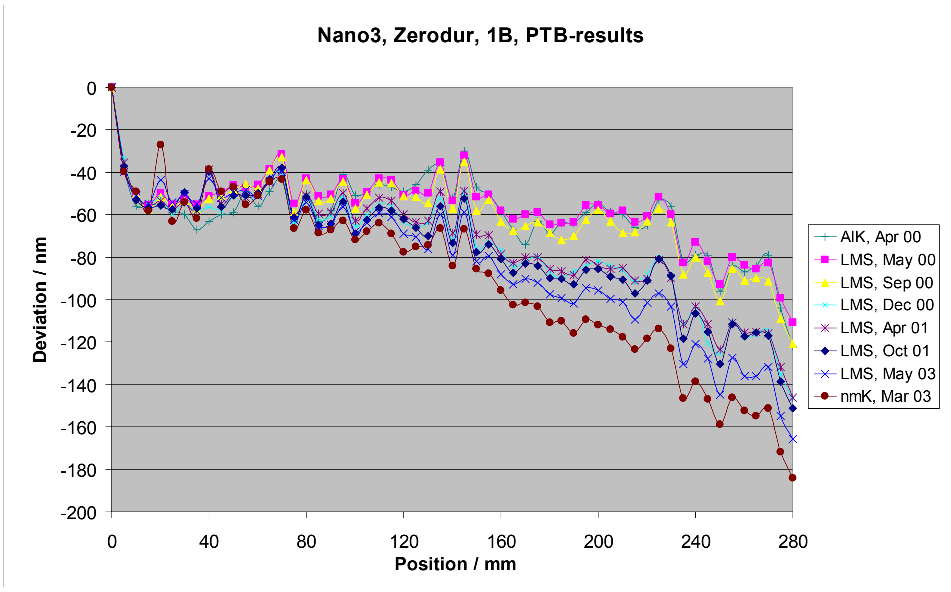

Fig. 11: Results of successive calibrations of the pilot laboratory on the Zerodur line scale: deviations from nominal values for every 5 mm line, Measurand 1B.

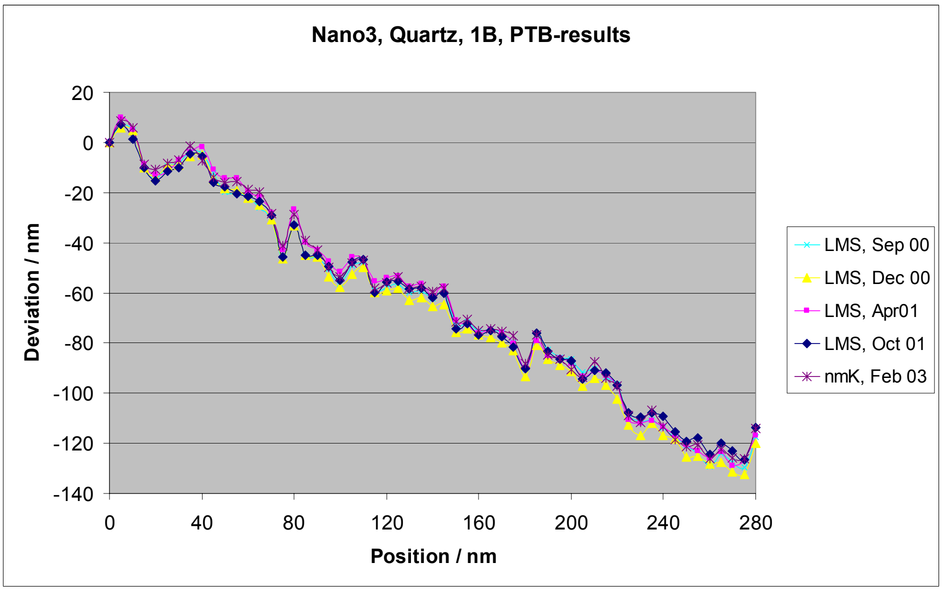

Fig. 12:Results of successive calibrations of the pilot laboratory on the quartz line scale: deviations from nominal values for every 5 mm line, Measurand 1B.

To better illustrate the reproducibility of the individual line position measurements, the deviations from one measurement result chosen as an arbitrary reference (Oct 2001) are shown in Fig. 13.

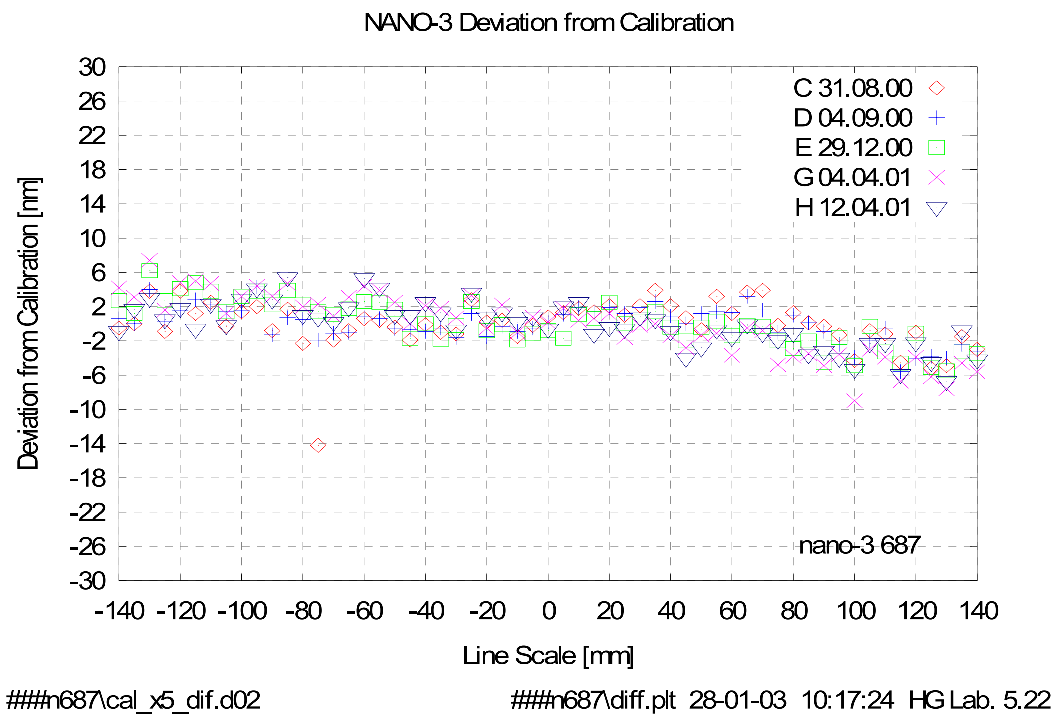

Fig. 13:Results of successive calibrations of the pilot laboratory on the quartz line scale: deviations from an arbitrarily chosen reference measurement (Oct 2001), Measurand 1B.

The analogous graph for the recalibration results on the Zerodur line scale however looks different, see Fig. 14.

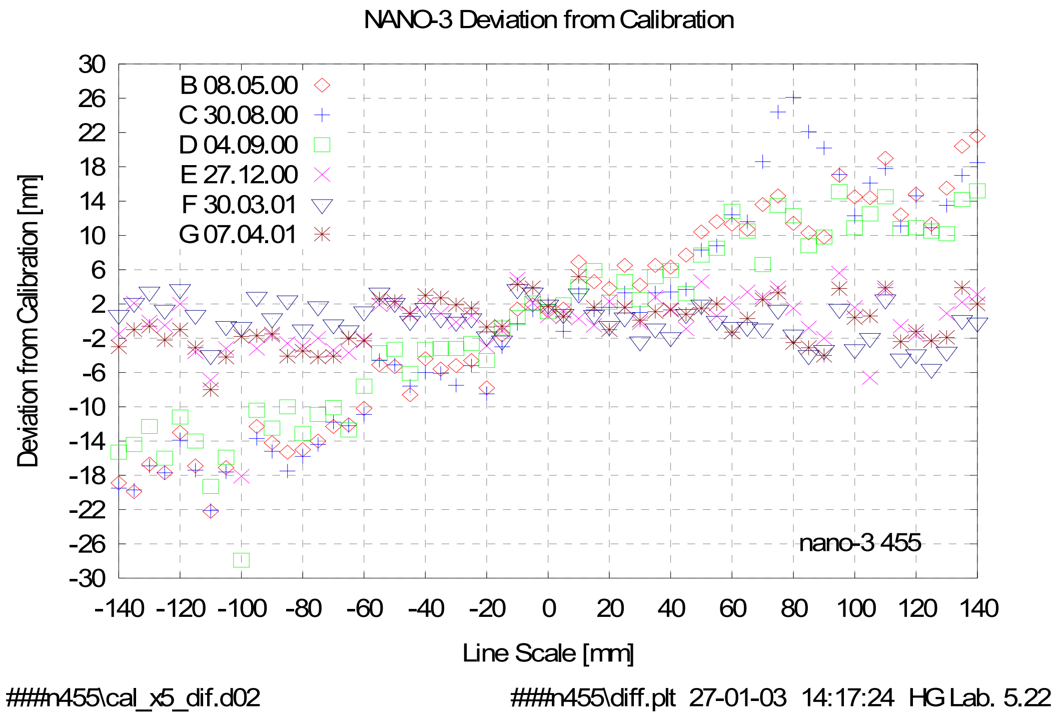

Fig. 14: Results of successive calibrations of the pilot laboratory on the Zerodur line scale: deviations from an arbitrarily chosen reference measurement (Oct 2001), Measurand 1B. The differences between 30.08.00 and 04.09.00 at around 80 mm are due to intermediate cleaning of the scale, which had been necessary to remove contamination.

Figure 14 indicates a discontinuous length change of the standard between September and December 2000. However, the observed relative length scale variations are not yet significant in view of its estimated uncertainty of $U_{95\%}=0{,}13\cdot 10^{-6}$. It would therefore be quite interesting to have some additional information about possible reasons for the observed length changes (relaxation processes, shock event influences during transport, ...).

6.1 TRANSPORTATION MONITORING OF THE CIRCULATED STANDARDS

The inner transportation suitcase of the Nano3 box contained battery operated data logging sensors[11] to continuously monitor temperature, humidity, shock events and suitcase open/close actions over time. Typically temperature and humidity data were measured every 15 minutes. With these sensors it was possible to some extent to monitor and analyse the transportation conditions of the line scale standards. Three simple shock event sensors were adjusted to record acceleration events larger than about 1 g and they were mounted along three orthogonal axes within the inner transportation suitcase.

An example of the applicability of the data loggers for transportation monitoring is given in Fig. 15. Shown is the transport from Canada to Germany in August 2000, during which the largest temperatures of 47 °C were measured inside the transportation box. It could be concluded, that this temperature increase took place on August 27th at Frankfurt airport, when the box was neither moved nor opened (assumed to be exposed to sun in a hall of the carrier service). Because re-calibrations of the PTB were started on August 30th, it is likely, that these calibration results were influenced by thermal relaxation behaviour of the

[11] HOBO type data loggers from Onset, USA: http://www.onsetcomp.com/

Zerodur line scale, see remarks in section 2.4.

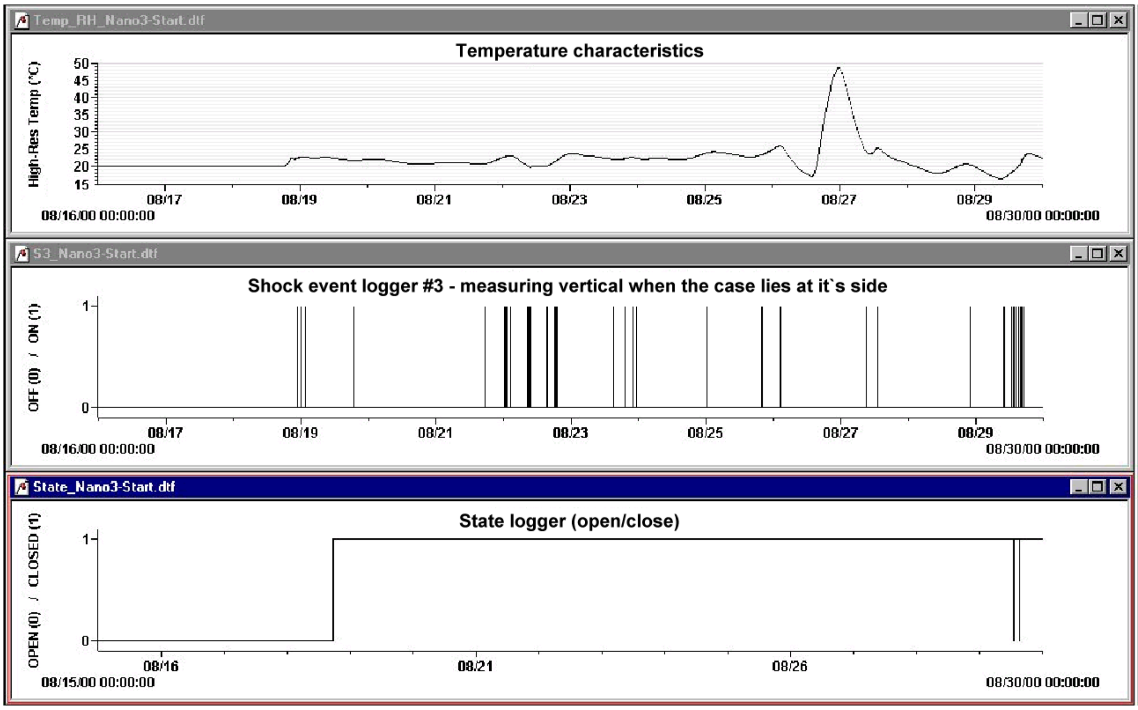

Fig. 15: Example of transport monitoring by data loggers for temperature, humidity, shock events and open/close events. Shown are data logged during transportation from NRC to PTB in August 2000, during which an extreme temperature increase up to 47 °C was observed.

Figure 16 shows the temperature and humidity record of the 2nd loop of the circulation from September to December 2000. The PTB re-calibrations were performed immediately after the standards were received on Dec. 22nd. The day before the line scales were cooled down to about 0 °C, thus the re-calibrations results might have been influenced as in Sep. 2000 by the thermal hysteresis behaviour, but now with different sign. The hysteresis superimposed on the long-term length contraction of the material can therefore be regarded as one possible explanation for the apparent jump in the length scale of the Zerodur standard, as indicated in Fig. 14.

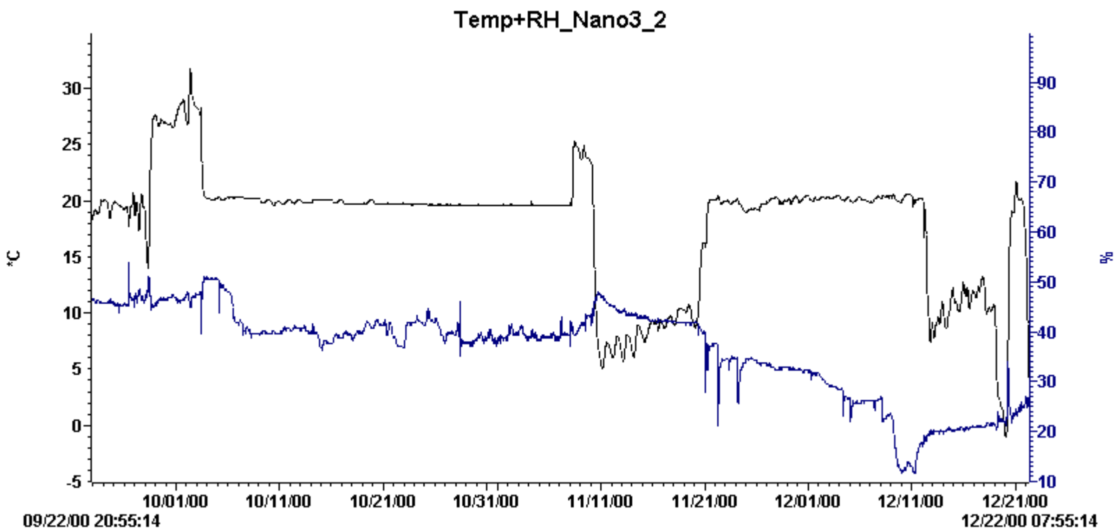

Fig. 16: Monitoring of temperature and humidity during 2nd loop from Sep. to Dec. 2000.

6.2 *DRIFT CORRECTION FOR ZERODUR*

Although it is known that Zerodur shows a long-term length reduction caused by a relaxation behaviour, which can be described by an exponential decrease, our data are not sufficient to apply a meaningful exponential decay approximation. Instead, the drift data is approximated by a linear model, see Fig. 17.

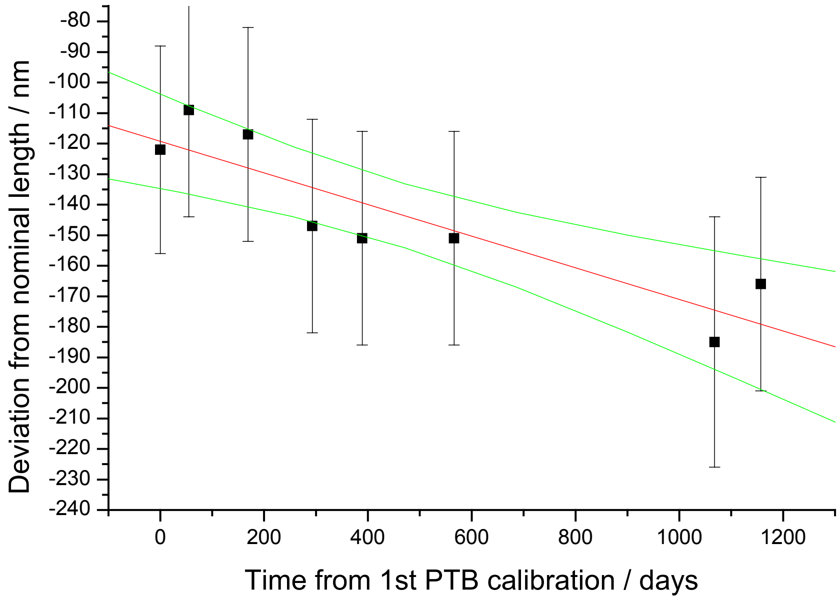

Fig. 17: Linear drift approximation to PTB data of 280 mm Zerodur scale (95% confidence bands).

Linear model: dl_{280} = -(119±18) nm + (-0,052±0,031) · d; d in days

Linear model: dl_{280} = -0,052 nm/d (-19 nm/a) Udl_{280} = 0,031 nm/d (11 nm/a)
dl/l = $-1{,}86\cdot10^{-10}$ /d Udl/l = $1{,}11\cdot10^{-10}$ /d
dl/l = $-6{,}8\cdot10^{-8}$ /a Udl/l = $4{,}1\cdot10^{-8}$ /a

The participants' data on Zerodur were corrected and referred to 1st LMS result from 8th of May 2000, see Table 4 (uncertainty of drift correction over whole circulation period of 695 days (LNE as last participant): 21,5 nm at 280 mm or $7{,}7\cdot10^{-8}$ (k=2)):

Table 4: Drift correction data for participants result on 280 mm Zerodur scale *(abs., rel.)*

NIST: 40 days	2,1 nm; 7,44E-09	SP: 420 days	21,8 nm; 7,81E-08
METAS: 130 days	6,8 nm; 2,42E-08	IMGC: 555 days	28,9 nm; 1,03E-07
CMS/ITRI: 165 days	8,6 nm; 3,07E-08	VNIIM: 615 days	32,0 nm; 1,14E-07
NIM: 205 days	10,7 nm; 3,81E-08	NMIJ: 655 days	34,1 nm; 1,22E-07
MIKES: 370 days	19,2 nm; 6,88E-08	LNE: 695 days	36,1 nm; 1,29E-07

It should be pointed out that the analysis of the participants data on the Zerodur standard is not crucially dependent on the application of the linear drift correction model. Application of a stepwise correction based on the data in Fig. 17 for example yields quite similar results, especially concerning reference values and exclusion of participants with $|E_n|$-values < 1.

7 UNCERTAINTY EVALUATIONS

The uncertainty of all measurement data should be evaluated according to the *ISO Guide to the Expression of Uncertainty in Measurement*. In order to achieve a better comparability of the uncertainty budgets some possible influence parameters and notations were given in the technical protocol. The participants were encouraged to include all known and significant influence parameters for their applied methods. The following list could be used as an indication of possible influence parameters, however it does not claim to be complete:

Possible contributions from **line position sensing** technique:

δ_{Eres}	Resolution of edge detection
s_E	Repeatability of edge detection
δ_{Edef}	Edge geometry influence (roughness, parallelism)
δ_{lpos}	Influence of adjustment of measurement line
δ_{lwin}	Influence of adjustment of measurement window or slit length
δ_{Efoc}	Influence of focus variation
$\delta_{E\lambda}$	Influence of illumination light wavelength
δ_{Epol}	Influence of illumination light polarization
δ_{Ecoh}	Influence of illumination light coherence
Mag	Microscope magnification (or sensitivity of other line position sensing device)
δ_{Enon}	Nonlinearities of position sensing technique
δ_{Ealig}	Microscope axis alignment
δ_{Ealg}	Influence of line edge detection algorithm, possible asymmetry of line profiles, line shape
δ_{Erev}	Influence of measurement in reversed orientation

Possible uncertainty contributions from interferometric **displacement measurement** technique:

$\delta\lambda_o$	vacuum wavelength of light source used for displacement measurement
δn_{air}	Index of refraction of air[12]
δt_{air}	Air temperature
δp_{air}	Air pressure
δRH_{air}	Air humidity
δx_{CO2}	Air CO_2 concentration
δl_{Res}	Interferometer resolution
δl_{NL}	Interferometer nonlinearity (polarisation mixing, etc.)
δl_{DP}	Interferometer deadpath influences (temperature variation, etc.)
δl_{MP}	Variation of measurement path in one orientation (normal, meander, random, ..)
δl_{Drift}	Drift influence (forward, backward measurement)
δl_{Rev}	Influence of measurement in reversed orientation
δl_{Ai}	Errors due to Abbe offsets and pitch and yaw of translation stages

[12] If the index of refraction was determined by the parameter method according to Edlen, the updated version of the formula should have been applied as published in: G. Bönsch, E. Potulski, Metrologia, 1998, **35**, 133-139. The estimated combined standard uncertainty of the quoted formula itself is $1*10^{-8}$.

δl_{Si} Errors of scale alignment

δl_{Ii} Cosine errors of interferometer alignment

Possible uncertainty contributions from **scale properties**:

$\delta\alpha_{Z,\,Cr}$ Linear coefficient of thermal expansion of scale material

$\delta\Delta t_s$ = (t_s - 20) is the difference of the scale temperature t_s in °C during the measurement from the reference temperature of 20 °C

$\delta\kappa_{Z,\,Cr}$ Linear coefficient of compressibility of scale material

δh Flatness deviation of scale graduation surface

δ_{supp} Influence of support conditions

The deviations *dl* from nominal length had to be measured and to be expressed as a function of input quantities $x_{i\ (i=1,2\ ,\ \ldots,\ N)}$

$$dl = f(x_i)\,, \tag{1}$$

The combined standard uncertainty $u_c(dl)$ is the quadratic sum of the standard uncertainties of the input quantities $u_i(x_i)$ each weighted by a sensitivity coefficient c_i

$$u_c^{\,2}(dl) = \sum_i c_i^{\,2} u_i^{\,2}(x_i), \text{with}\, c_i = \frac{\partial dl}{\partial x_i}\,. \tag{2}$$

In some cases also higher order terms of equation (2) might have to be taken into account. If correlation between input quantities is present the correlation coefficients should be considered.

The participants were required to report their measurement uncertainty budget in a table with the format according to the scheme below. "Distrib." is the type of distribution of the probability of the input quantity (N=normal, R=rectangular, T=triangular, etc.), ν_i is the number of degrees of freedom of $u(x_i)$, ν_{eff} is the effective number of degrees of freedom of the combined standard uncertainty $u_c(dl)$.

Example scheme:

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl / \partial x_i$	$u_i\,(dl)$ / nm
Edge detection reproduc. s_E	N	3 nm	10	1	3
Cosine error scale alignment	R	140 µrad	>100	-	$10^{-8}\,L$
...	...	...	...	...	...

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(dl)$ =

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

Expanded uncertainty: $U_{95}(dl)$ =

8 REFERENCE VALUES AND DEGREES OF EQUIVALENCE

Because the participants of the Nano3 comparison reported largely differing measurement uncertainties, the reference values (x_{ref}) for this line scale comparison were calculated as the **weighted mean** of all measurements (x_i). The weight factors are $u^{-2}(x_i)$. For each standard and for each measurand a reference value was calculated. To calculate the reference values, only those results which followed the $|E_n| \leq 1$ criterion were used [13]. Measurements with E_n values larger than one have been omitted one by one for the calculation of the reference value. Due to this procedure all values contributing to the reference value exhibited E_n values smaller than one.

Reference value:
$$x_{ref} = \frac{\sum_{i=1}^{n} \frac{1}{u^2(x_i)} x_i}{\sum_{i=1}^{n} \frac{1}{u^2(x_i)}} \tag{3}$$

Combined standard uncertainty:
$$u_c(x_{ref}) = \frac{1}{\sqrt{\sum_{i=1}^{n} u^{-2}(x_i)}} \tag{4}$$

Degree of freedom:
$$\nu_{eff}(x_{ref}) = \frac{u_c^4(x_{ref})}{\sum_{i=1}^{n} \frac{u_i^4(x_{ref})}{\nu_{eff}(x_i)}} \quad \text{with} \quad u_i(x_{ref}) = |c_i| \cdot u(x_i) = \frac{u^{-1}(x_i)}{\sum_{i=1}^{n} u^{-2}(x_i)} \tag{5}$$

Expanded uncertainty:
$$U_{95}(x_{ref}) = 2 \cdot u_c(x_{ref}) \tag{6}$$

E_n-value:
$$E_n = \frac{1}{k} \frac{x_{lab} - x_{ref}}{\sqrt{u^2_{xlab} - u^2_{xref}}} \quad ; \text{k=2} \tag{7}$$

The minus sign in the denominator of (7) is used because there is a correlation between a single measurement result and the reference value. If the E_n-criterion is missed by one participant result, either the measurement value showed some systematic deviation or the uncertainty budget calculation does not include all contributions in the correct manner.

The Birge ratio:
$$R_B = \frac{u_{ext}}{u_{in}} \tag{8}$$

with
$$u_{ext} = \sqrt{\frac{\sum_{i=1}^{n} \left[\left(x_i - x_{ref} \right) / u_i \right]^2}{(n-1) \sum_{i=1}^{n} u^{-2}(x_i)}} \quad \text{and} \quad u_{in} = 1 / \sqrt{\sum_{i=1}^{n} u^{-2}(x_i)} \tag{9}$$

is often calculated to check the statistical consistency of a comparison. It compares the

[13] see: W. Wöger, Remarks on the E_n –Criterion Used in Measurement Comparisons in PTB-Mitteilungen 109 1/99 p. 24

observed spread of results with the spread of the estimated uncertainty. $R_B > 1$ indicates an underestimation of measurement uncertainty by at least one participant, while $R_B < 1$ indicates an overestimation of measurement uncertainty by at least one participant. The expectation value of R_B for normal distributions is 1. The results may *not* be assumed to be normally distributed if $\chi^2_{\min} > \nu + k \cdot \sqrt{2\nu}$ or $R_B > \sqrt{1+\sqrt{8/\nu}}$ for a significance level of 95% (k=2, ν=n-1). If the results were not be found to be consistent, the participants had to be informed about the inconsistency and possible reasons had to be discussed.

The degree of equivalence (DoE) of each laboratory with respect to the reference value is given by a pair of values DoE(D_{ir},U_{ir}), the difference from the reference value and its uncertainty:

$$D_{ir} = x_i - x_{ref} \quad \text{and} \quad U_{ir}^2 = 2*(u_i^2 + u_r^2) \qquad (10)$$

with U_{ir} as the expanded uncertainty of DoE ($k = 2$).

9 RESULTS

In the following the results received from all participants for all measurands asked for are presented. Besides the measured values for the deviations from nominal lenghts *dl*, the combined standard uncertainty *u*, the degree of freedom ν_{eff} and the expanded uncertainty U(k=2) is given, where possible. To calculate the $|E_n| \le 1$ criterion, the expanded uncertainty U with a coverage factor of k = 2 is used. Measurements with E_n values larger than 1 have been omitted one by one for the calculation of the reference values, as described in the following sections.

As explained before, the pilot laboratory has determined its measurement results on the line scale standards by means of the LMS mask comparator. This instrument serves as PTB's reference instrumentation within the Nano3 comparison. However, for all calibrations on the main graduations, the measurement results gained by means of PTB's new vacuum line scale comparator, called nanometer comparator (nmK), are shown for information purposes only. The measurement values of the nanometer comparator were **not** taken into account for calculation of the reference values.

9.1 RESULTS ON LINE SCALES, MEASURAND 1A: DEVIATION FROM 280 MM LENGTH

The following Figures 18-20 show the participants' results on the 280 mm principal length of the main graduations on the two different line scale standards. They are plotted on one page to allow an easy visual comparison of the graphs.

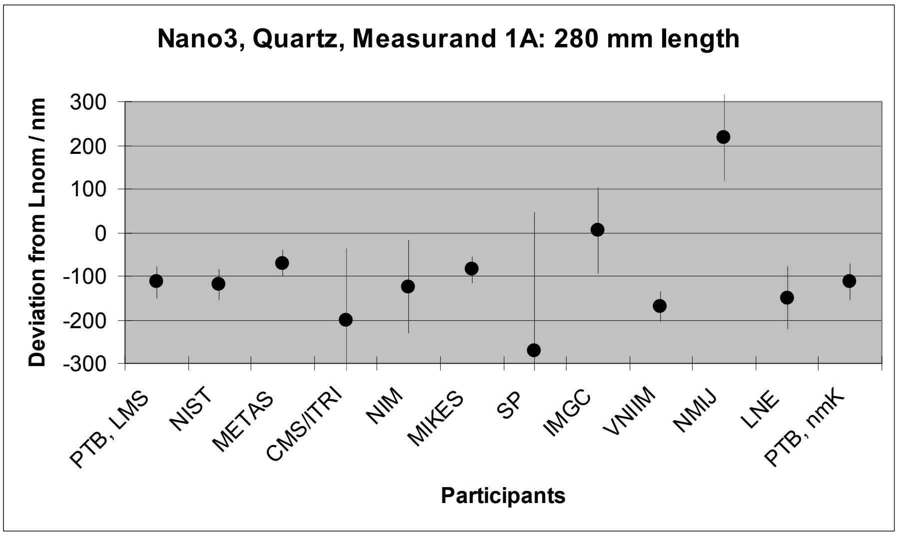

Fig. 18: Results on quartz scale, measurand 1A: Deviations from 280 mm principal length.

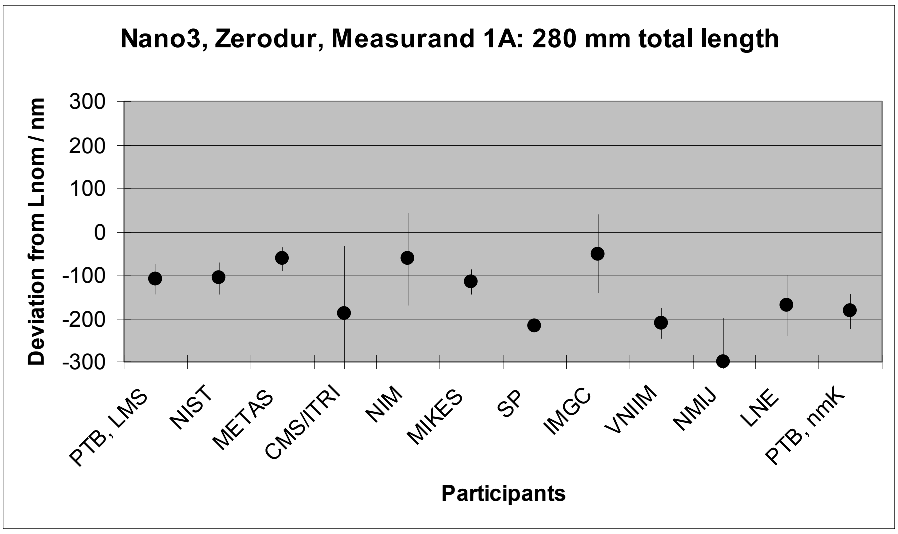

Fig. 19: Original results on Zerodur scale, measurand 1A: Deviations from 280 mm length.

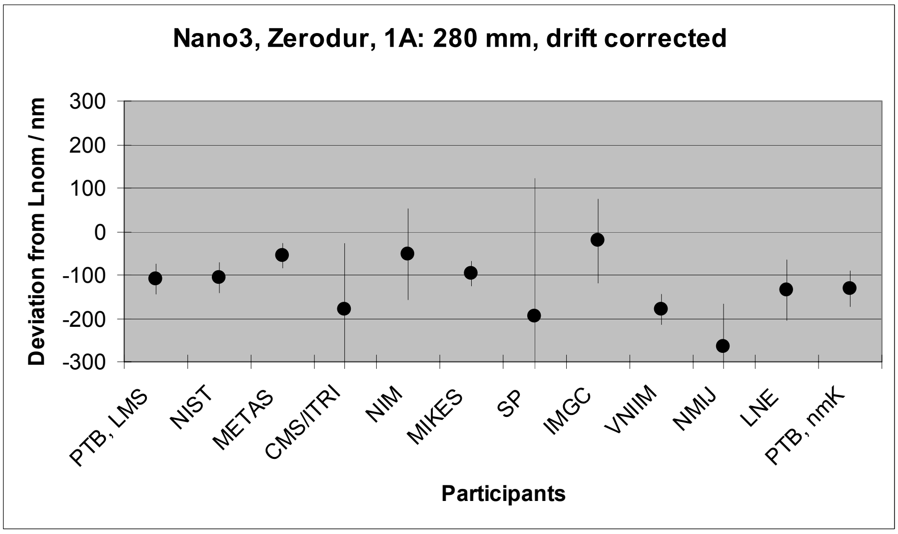

Fig. 20: Drift corrected results on Zerodur scale, measurand 1A: Deviations from 280 mm length.

In Figures 18-20, the characteristic signature of the participants results is very similar on both scales, only the results of NMIJ do not follow the common trend. This is a clear indication, that the observed differences on one of the scales do already reliably describe different realizations of the length scale at the participating NMIs. As expected, the similarity between the results is even better for the drift corrected results on the Zerodur scale.

In Table 5, the individual results and the determined weighted mean reference value on the quartz line scale data are shown after 2 loops for exclusion of participant results with $|E_n|$ larger than one were performed. We decided not to exclude participants results which showed only slightly increased En-values from generation of reference value. See the dicussion in Annex E for more information on this specific point.

Table 5: Participants results and reference value on Quartz scale, Task 1A, no drift corr.

Nano3, Quartz, Task 1A, Deviations from 280 mm principal length, original values							
Participant	dl_{Orig} / nm	u_c / nm	ν_{eff}	U / nm	$E_{n, Orig}$	D_{ir} / nm	U_{ir} / nm
PTB, LMS	-114,0	18,0	19	37,5	-0,53	-18,2	34,2
NIST	-119,1	14,7	7	34,7	-0,75	-23,3	31,1
METAS	-70,0	15,0	46	30,2	1,00	25,8	26,0
CMS/ITRI	-202,0	83,0	73	164,0	-0,65	-106,2	163,3
NIM	-125,0	53,0	84	106,0	-0,28	-29,2	104,9
MIKES	-85,2	14,3	27	29,4	0,43	10,6	25,0
SP	-270,0	152,0	56	317,3	-0,55	-174,2	316,9
IMGC	5,0	48,0	28	99,0	1,03	100,8	97,8
VNIIM, **	*-170,0*	*15,0*	*13*	*35,0*	*-1,94*	*-74,2*	*38,2*
NMIJ, *	*218,0*	*50,0*	*48*	*100,0*	*3,10*	*313,8*	*101,2*
LNE	-150,0	36,0	103	72,0	-0,77	-54,2	70,3
Ref. value	**-95,8**	**7**		**15,4**	calculated as weighted mean		
PTB, nmK	-114,0	20,0	22	41,2	-0,41	-18,2	44,0

Selection scheme for calculation of reference value:

	Ref. Value	Birge-Ratio	
1st loop, *	-101,5	1,35	=> excluding NMIJ (E_n=3,23)
2nd loop, **	-107,9	0,95	=> excluding VNIIM (E_n=-1,94)
final	-95,8	0,70	=> no more exclusions, although IMGC: E_n=1,03

The uncertainty of the reference value for the quartz scale is smaller than for Zerodur, because no drift correction had to be applied for the quartz standard.

In Table 6, the individual results and the determined reference value of the drift corrected data for Zerodur are shown. Two loops of exclusion of participant results with E_n larger than one were performed. The uncertainty of the reference value was calculated by the geometric sum of the uncertainty of the weighted mean value and the attributed uncertainty contribution due to drift correction. The uncertainty U_{Dir} for the difference $D_{ir} = x_i - x_{ref}$ was calculated according to $u_{Dir} = [u_{xi}^2 - u_{weighted\_mean}^2 + u_{drift}^2]^{1/2}$ for those participants' results which contributed to the calculation of the reference value and therefore are correlated and according to $u_{Dir} = [u_{xi}^2 + u_{weighted\_mean}^2 + u_{drift}^2]^{1/2}$ for those participants' results which were excluded from calculation of the weighted mean reference value.

Table 6: Participants results and reference value on Zerodur scale, Task 1A, drift corr.

Nano3, Zerodur, Task 1A, Deviations from 280 mm principal length, drift corrected							
Participant	dl_{Drift} / nm	u_{c} / nm	ν_{eff}	U / nm	$E_{\mathrm{n},\,drift}$	D_{ir} / nm	$U_{D\,\mathrm{ir}}$ / nm
PTB, LMS	-109,0	18,0	19	38,0	-0,50	-20,6	41,3
NIST	-105,7	14,8	7	35,0	-0,45	-17,3	38,5
METAS	-56,2	13,7	37	27,7	1,00	32,1	32,0
CMS/ITRI	-179,4	82,0	71	163,0	-0,56	-91,0	163,8
NIM	-52,3	53,0	84	106,0	0,34	36,0	107,2
MIKES	-96,3	14,3	27	29,4	-0,24	-7,9	33,5
SP	-194,2	151,0	56	318,0	-0,33	-105,8	318,4
IMGC	-22,1	47,0	54	97,0	0,67	66,2	98,3
VNIIM, *	*-179,0*	*15,0*	*13*	*35,0*	*-2,06*	*-90,6*	*44,0*
NMIJ, **	*-265,9*	*50,0*	*48*	*100,0*	*-1,72*	*-177,6*	*103,5*
LNE	-134,9	35,0	97	70,0	-0,65	-46,5	71,8
Ref. value	**-88,4**	**11**		**26,6**	calculated as weighted mean		
PTB, nmK	-131,3	20,0	22	41,2	-0,88	-42,9	49,1

Selection scheme for calculation of reference value based on drift corrected data:			
	Ref. value	Birge-Ratio	
1st loop, *	-105,8	1,18	=> excluding VNIIM (E_{n}=-1,88)
2nd loop, **	-92,5	1,14	=> excluding NMIJ (E_{n}=-1,71)
final	-88,4	1,11	=> no more exclusions although METAS: E_{n}=1,004
Drift correction uncertainty contribution for reference value 22 nm (k=2):			22
Statistical uncertainty contribution for weighted mean reference value 15 nm:			15

9.2 RESULTS ON LINE SCALES, MEASURAND 1B: 280 MM MAIN GRADUATION, 5 MM STEP

In the following figures and tables, the results for the most important measurand of this comparison, namely for the 280 mm main graduation, to be measured at every 5 mm line (or at least every 10 mm) are shown and analysed, beginning with the **quartz scale**.

Fig. 21 shows the deviations from the nominal positions for every participant and the weighted mean, calculated on the basis of all measurement data. However, as already stated before not taking into account the results from PTB's nanometer comparator. Some measurement results (NMIJ, IMGC, …) seem not to coincide with the majority of results. However, to analyze the measurement results in detail, the deviations have to be compared including its uncertainties. Fig. 22 therefore shows the E_{n}-values calculated for all participants. The exclusion of results with E_{n} -values larger than one was based on an analysis of the mean E_{n} -value of all 56 line position data and the number of E_{n} -values exceeding one (exclusion if more than one third of the values are larger than 1). The different loops are described below:

1st loop: NMIJ: mean E_{n} -value = 2,23; 42 $|E_{\mathrm{n}}|$-values > 1 => excluding NMIJ
2nd loop: VNIIM: mean E_{n} -value = -1,34; 41 $|E_{\mathrm{n}}|$-values > 1 => excluding VNIIM
3rd loop: IMGC: mean E_{n} -value = 0,85; 21 $|E_{\mathrm{n}}|$-values > 1 => excluding IMGC

Figure 23 shows the final distribution of E_{n} -values after the exclusion of the 3 participants.

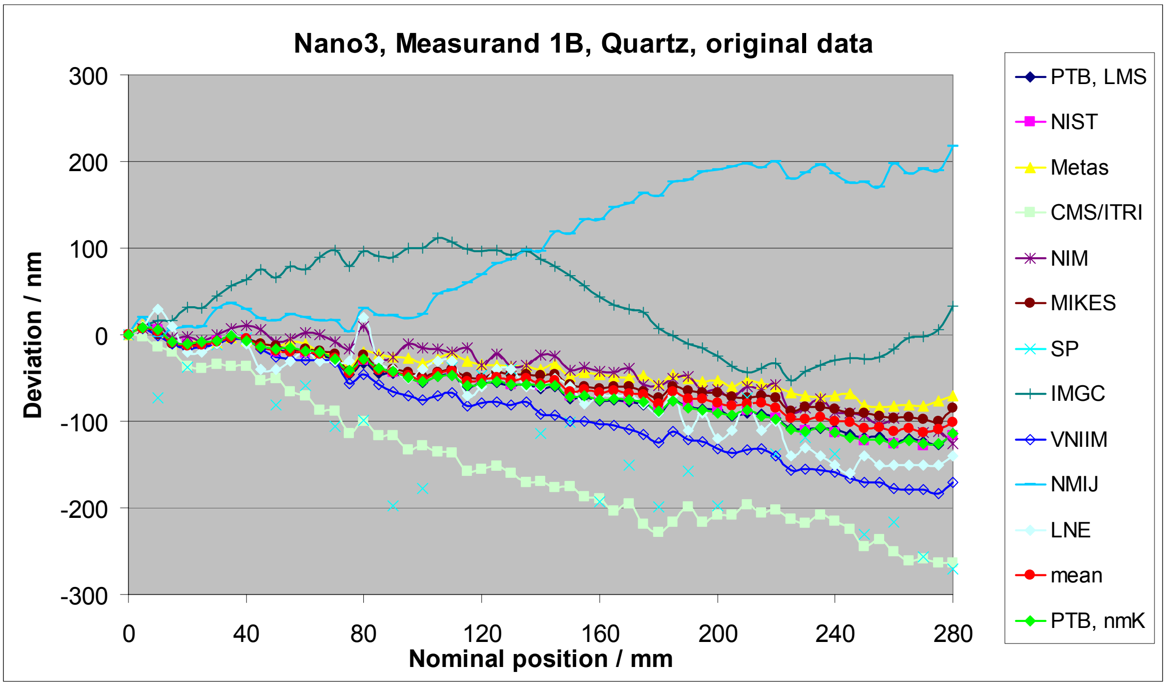

Fig. 21: Results on quartz scale, measurand 1B: 280 mm main graduation, 5 mm step. All values used for calculation of weighted mean.

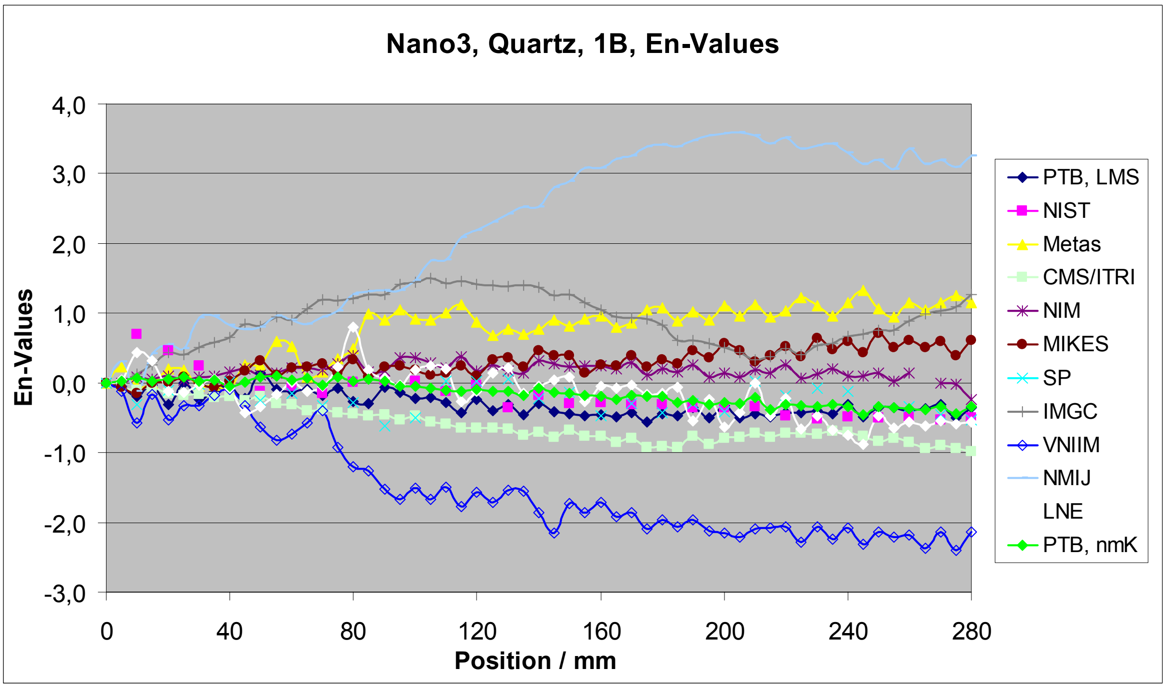

Fig. 22: E_n-values for results on quartz scale, measurand 1B: all participants evaluated.

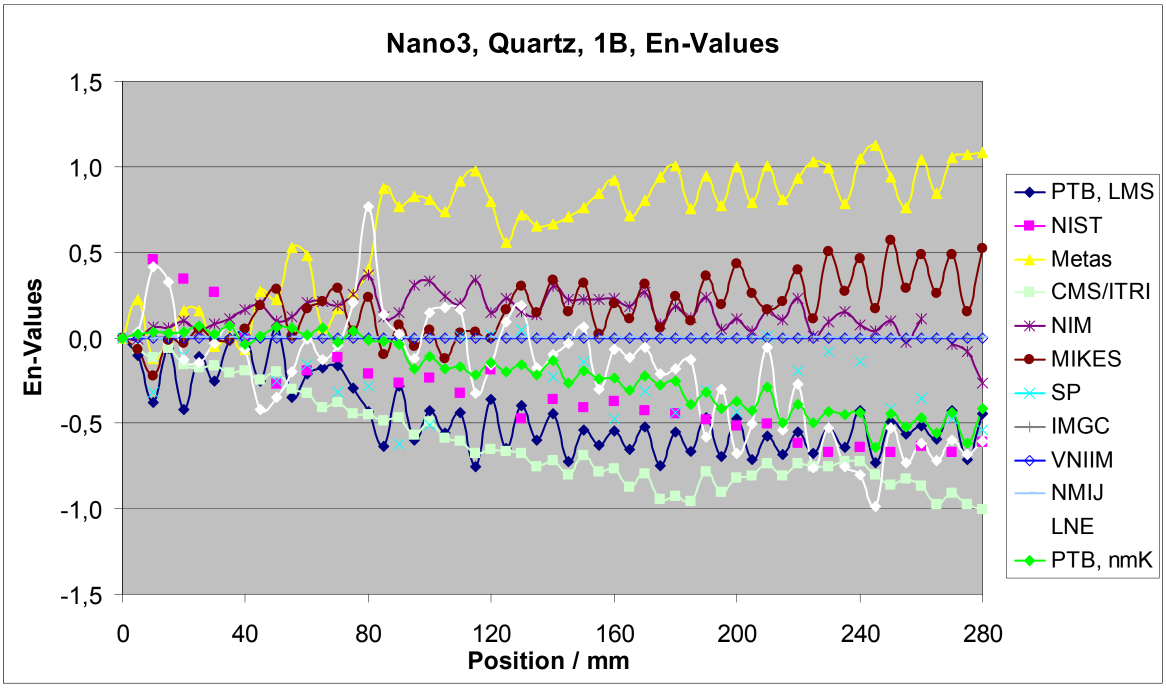

Fig. 23: E_n-values for results on quartz scale, measurand 1B: after exclusion of results with $E_n| > 1$.

In Fig. 23 with the exception of only a few $|E_n|$-values all others are smaller than one. These participants' results were used to calculate the weighted mean reference values, as shown in Figure 24.

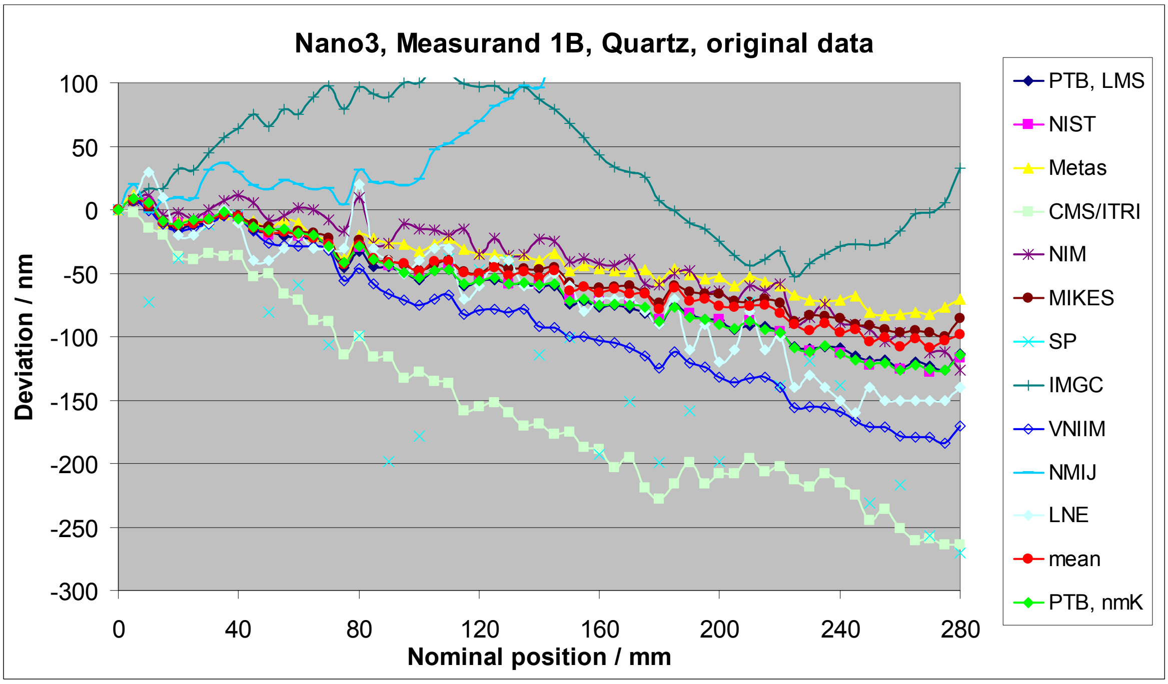

Fig. 24: Results on quartz scale, measurand 1B: 280 mm main graduation, 5 mm step. Calculation of weighted mean after exclusion of participants results with $|E_n| > 1$.

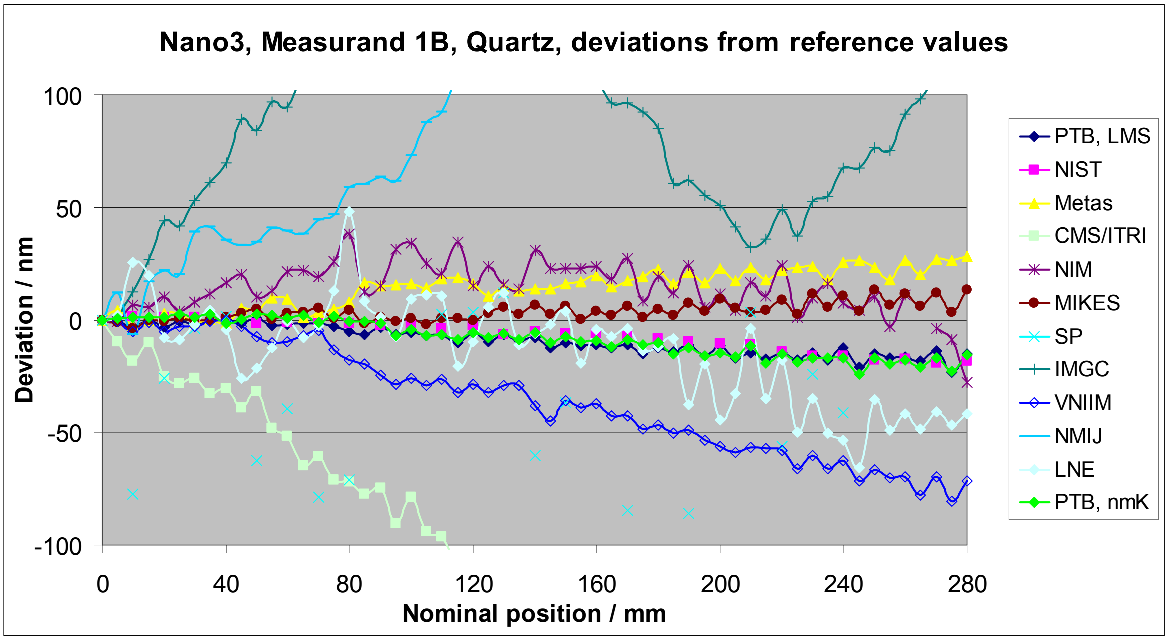

Fig. 25: Results on quartz scale, measurand 1B: deviations from reference values.

To calculate one characteristic value from a measurement data set of a participant which is representative for the length scale realization of that particular institute and which can in principle be used for length scale adjustments, linear regressions were performed on all data sets, including the weighted mean reference data. The resulting slopes of the regression lines (excluding zero point) were used as this characteristic parameter, describing the length scale realization. Table 7 gives an overview of the results.

Table 7: Participants results and slope reference value on quartz scale, Task 1B.

Nano3, Quartz, Task 1B: Deviations from nominal length on main graduation, 5 mm step											
Participant	$u_{c,const}$ / nm	$u_{c,l}$ / 10^{-6}	$\nu_{eff,280}$	$U_{c,const}$ / nm	$U_{c,l}$ / 10^{-6}	*slope* / 10^{-6}	$U_{stat,sl}$ / 10^{-6}	$U_{total,sl}$ / 10^{-6}	$E_{n,slope}$	D_{ir} / 10^{-6}	U_{Dir} / 10^{-6}
PTB, LMS	4,2	0,062	19	9	0,130	-0,467	0,018	0,131	-0,58	-0,07	0,13
NIST	2,4	0,050	7	6	0,118	-0,484	0,025	0,121	-0,79	-0,09	0,12
METAS	10,0	0,041	46	20	0,082	-0,300	0,018	0,084	*1,23*	*0,09*	*0,08*
CMS/ITRI	79,5	0,082	74	159	0,165	-0,898	0,062	0,176	*-2,92*	*-0,50*	*0,17*
NIM	51,4	0,047	84	103	0,094	-0,441	0,036	0,101	-0,51	-0,05	0,09
MIKES	8,6	0,041	27	18	0,085	-0,358	0,020	0,087	0,45	0,04	0,08
SP	115,0	0,350	56	242	0,735	-0,669	0,245	0,775	-0,36	-0,27	0,77
IMGC, ***	49,5	0,062	43	103	*0,129*	-0,402	0,132	0,184	-0,04	-0,01	0,19
VNIIM, **	3,2	0,044	13	7	*0,100*	-0,690	0,022	0,102	*-2,66*	*-0,30*	*0,11*
NMIJ, *	23,9	0,160	48	41	*0,322*	0,882	0,079	0,332	*3,81*	*1,28*	*0,33*
LNE	31,0	0,060	103	62	0,120	-0,603	0,054	0,131	*-1,66*	*-0,21*	*0,13*
Ref. values					**0,040**	**-0,394**	**0,018**	**0,044**	calculated as weighted mean		
PTB, nmK	20,0	0,007	22	41	0,015	-0,486	0,018	0,023	*-1,86*	*-0,09*	*0,05*
*), **), ***): Participants results excluded from calculation of reference values in subsequent loops											

In Table 7 on the left side the length-independent and length-dependent uncertainty contributions evaluated by all participants are given. On the right side the slopes of the regression lines, their statistical uncertainty (from an unweighted linear regression fit) and the resulting total uncertainty (as geometric sum of evaluated uncertainty and experimentally determined statistical uncertainty) for the measured slopes are shown together with the E_n-values and the differences of the slopes with respect to the slope of the reference data and their uncertainty (degree of equivalence). In calculation of U_{Dir}, correlation effects were taken into account for those participants results which contributed to the reference values. The D_{ir}-values can be used by the participants to adjust their length-dependent measurement contributions to be in agreement with the calculated length-dependency of the reference data. Table 7 also shows that, in addition to those 3 participants which had to be excluded from the generation of the reference data set, some more institutes estimated a too small length-dependent uncertainty contribution to be in agreement with the reference slope. On the other hand, IMGC, although excluded before, now shows a slope in agreement with the reference slope.

In addition to the length-dependent influences and their comparative analysis, it is also of interest to investigate the length-independent contributions within the comparison data. Figure 26 shows the deviations of measured line positions from the reference data set after elimination of the observed length scale differences, listed in Table 7.

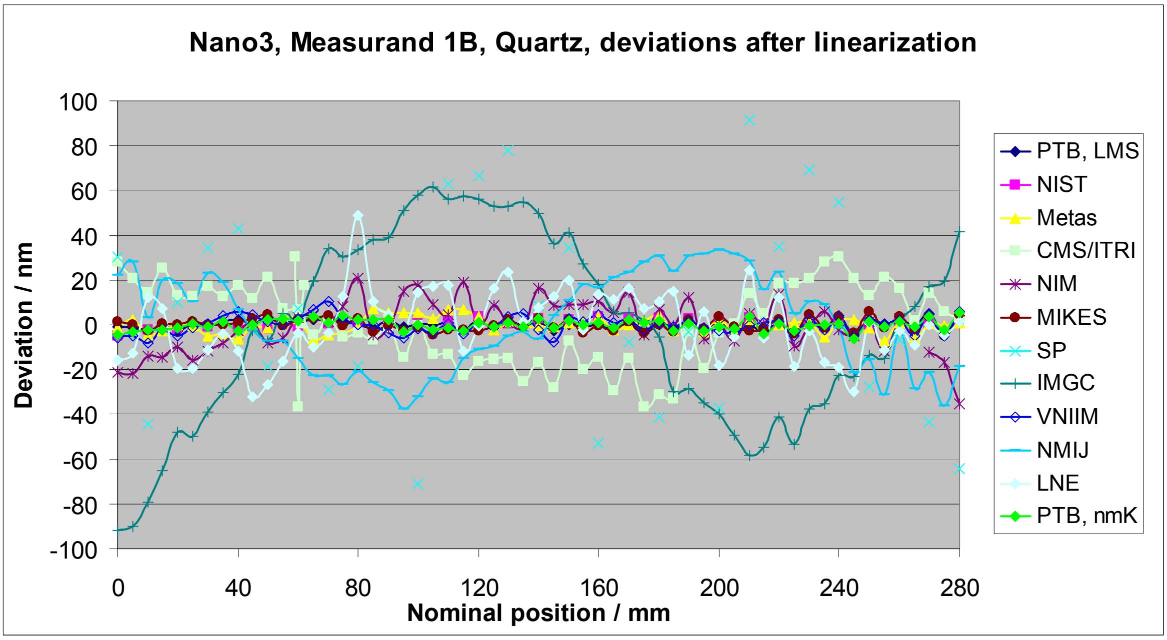

Fig. 26: Results on quartz scale, measurand 1B: deviations from reference data after linearization.

These deviations can now be analyzed and compared with the length-independent uncertainty estimations of the participants, as it is shown in Table 8. One can see, that two participants showed slightly larger 2σ-standard deviations as compared to their uncertainty estimations, whereas all other participants seemed to be too pessimistic in estimations of their length independent uncertainty contributions. This might also be due to the high quality of line scale graduations used for this comparison.

Table 8: Analysis of participants length-independent results on quartz scale, Task 1B.

Nano3, Quartz, Task 1B: Deviations from reference values after elimination of length scale differences												
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	NIM	MIKES	SP	IMGC	VNIIM	NMIJ	LNE	PTB, nmK
Max. dev. / nm	4,8	3,6	7,1	30,4	20,6	5,8	91,3	61,8	10,4	33,7	49,1	5,4
Min. dev. / nm	-4,1	-4,9	-7,1	-36,5	-35,4	-4,9	-101,7	-92,1	-8,1	-37,5	-32,2	-6,3
2s stddev./nm	4,2	4,0	7,1	35,5	22,5	5,5	99,1	84,6	7,7	43,0	30,9	4,7
Uconst / nm	9,0	5,7	20,0	159,0	103,0	17,7	242,0	103,0	7,0	41,0	62,0	41,0
(2s/U) / %	47%	71%	35%	22%	22%	31%	41%	82%	*110%*	*105%*	50%	11%

Finally, for those laboratories which quoted length-independent measurement uncertainties smaller than 20 nm a direct comparison with the reference data, again after elimination of linearity differences, is shown in Figure 27.

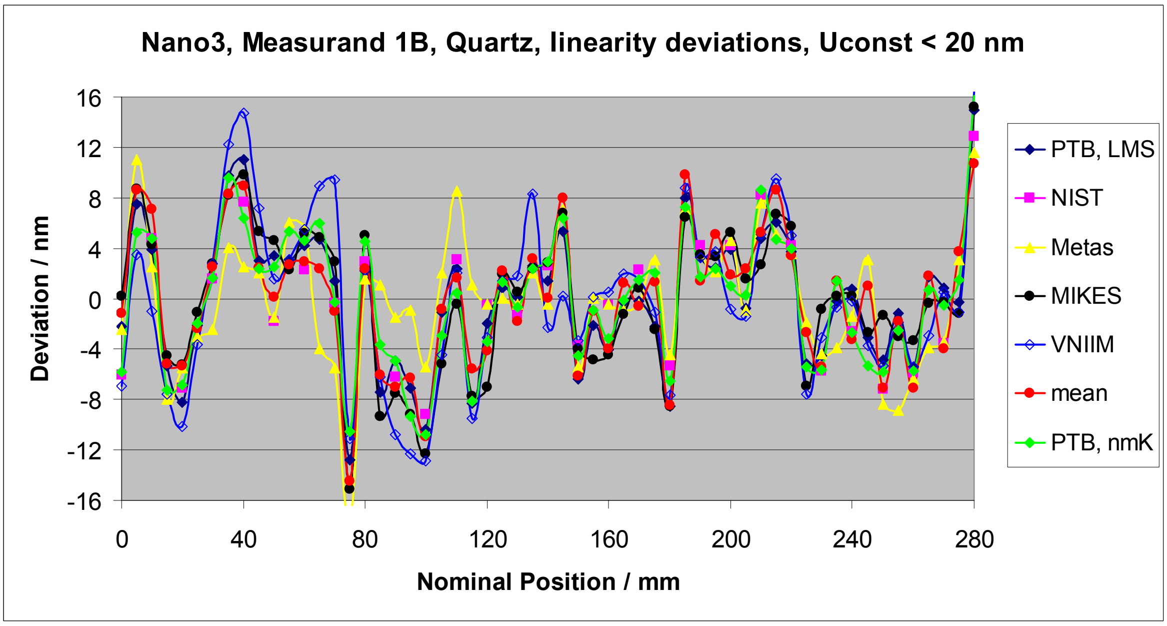

Fig. 27: Results on quartz scale, measurand 1B: deviations from linear regression lines, subset.

There is a remarkably good agreement of the results for the individual line positions. Line edge quality as well as cleanliness of the standard was sufficient to allow a meaningful comparison of individual line structure positions.

In the following an analogous presentation and analysis will be given for the results of the **Zerodur scale** for the measurand 1B.

Figure 28 illustrates the original, not for drift corrected measurement results, whereas Figure 29 shows drift-corrected values. The drift correction was performed in analogy to the description in section 9.1, based on the drift correction model explained in section 6.2. First, all participants results were corrected with the drift correction factors given in Table 4, i.e. no drift correction was applied to the data of the first participant (PTB, LMS) and a maximum relative drift correction of $+1{,}29\cdot10^{-7}$ (+36,1 nm @ 280 mm) was applied to the data of the last participant (LNE). These drift corrected data sets then were used to calculate the weighted mean reference values for all measured line structures. As the weights for calculation of the reference values, only the evaluated uncertainties given by the participants were used on the basis of the geometric sum of length-independent and length-dependent uncertainty contributions. In particular, it was not tried to additionally apply drift-dependent uncertainty contributions to the individual results of the participants.

However, in order to take into account the increased uncertainty of the comparison due to the drift behaviour of the Zerodur standard, an additional drift correction uncertainty contribution of $7{,}7\cdot10^{-8}$ (21,5 nm @ 280 mm) was applied to the calculated reference data. The En-values thus were calculated as: $E_n = (x_{lab}-x_{ref}) \,/\, [U_{xlab}^2 - U_{xref}^2 + U_{xref,drift}^2]^{1/2}$ for every measured line structure.

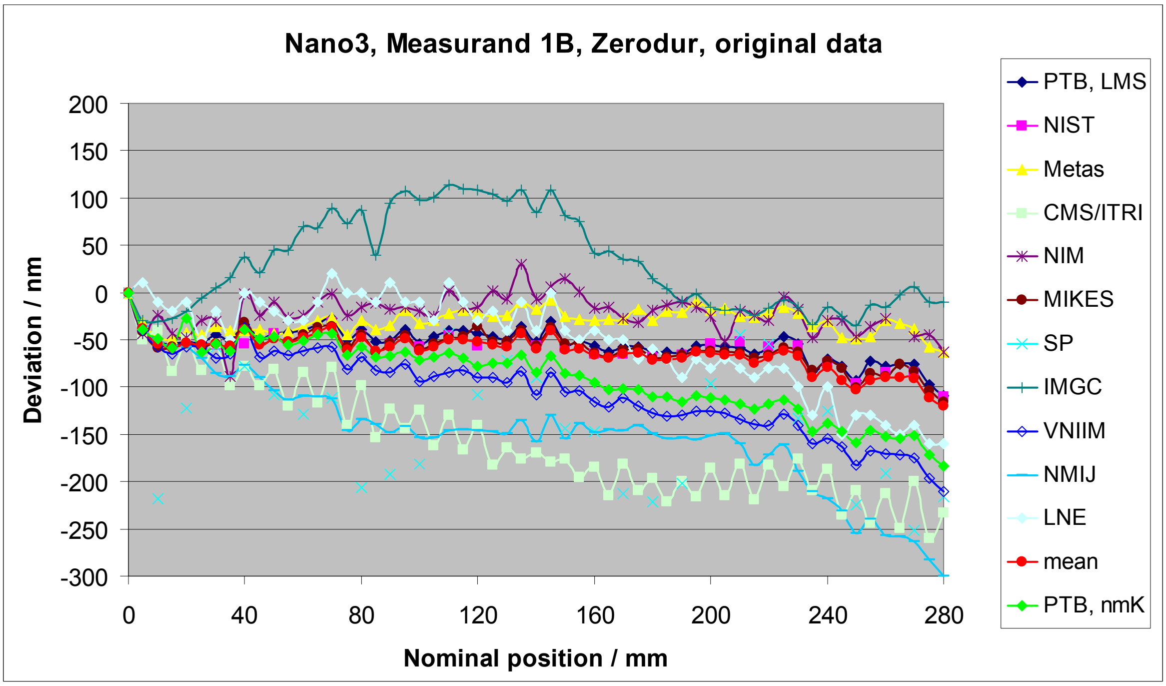

Fig. 28: Original results on Zerodur scale, measurand 1B: 280 mm main graduation, 5 mm step. All values used for calculation of weighted mean.

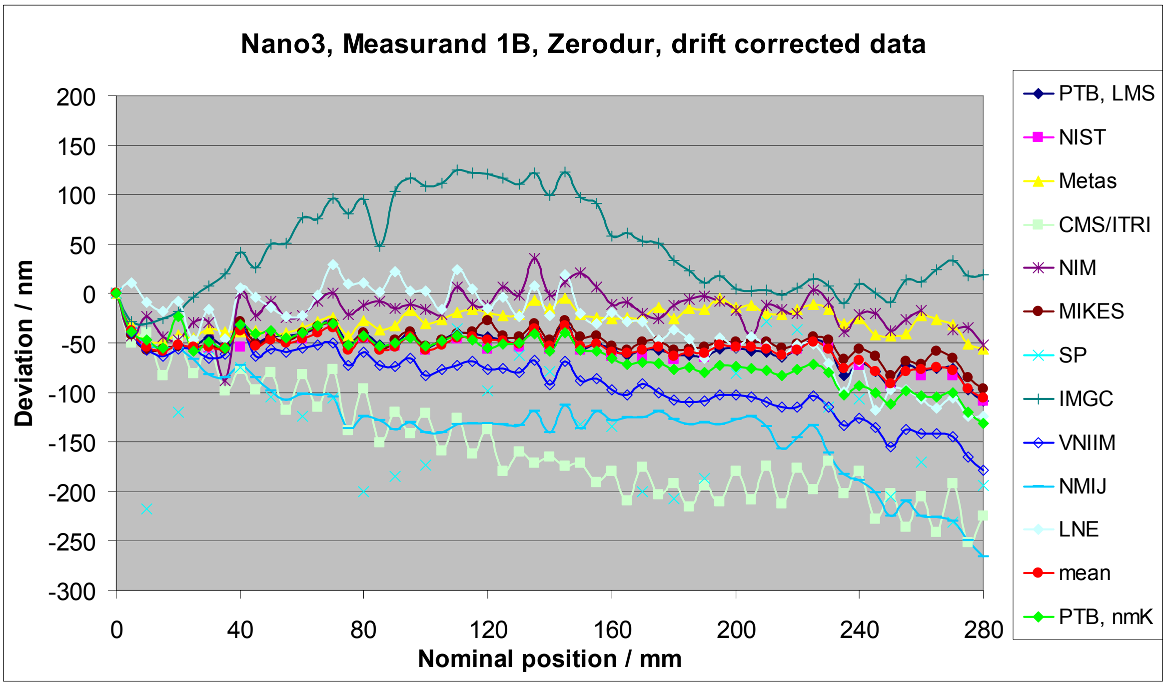

Fig. 29: Drift corrected results on Zerodur scale, measurand 1B: 280 mm main graduation, 5 mm step. All values used for calculation of weighted mean.

Again, as already stated for the measurand 1A, a similarity of the results on both scales is also visible for the measurand 1B, compare Fig. 29 and 21.

Fig. 30 shows the E_n-values calculated for the results of all participants. The exclusion of results with E_n-values larger than one was performed in a similar way as in the case of the quartz standard. The different loops are described below:

1st loop: VNIIM: mean E_n-value = -1,36; 43 $|E_n|$-values > 1 => excluding VNIIM

2nd loop: NMIJ: mean E_n -value = -1,28; 47 |E_n |-values > 1 => excluding NMIJ
3rd loop: IMGC: mean E_n -value = 0,85; 21 |E_n |-values > 1 => excluding IMGC

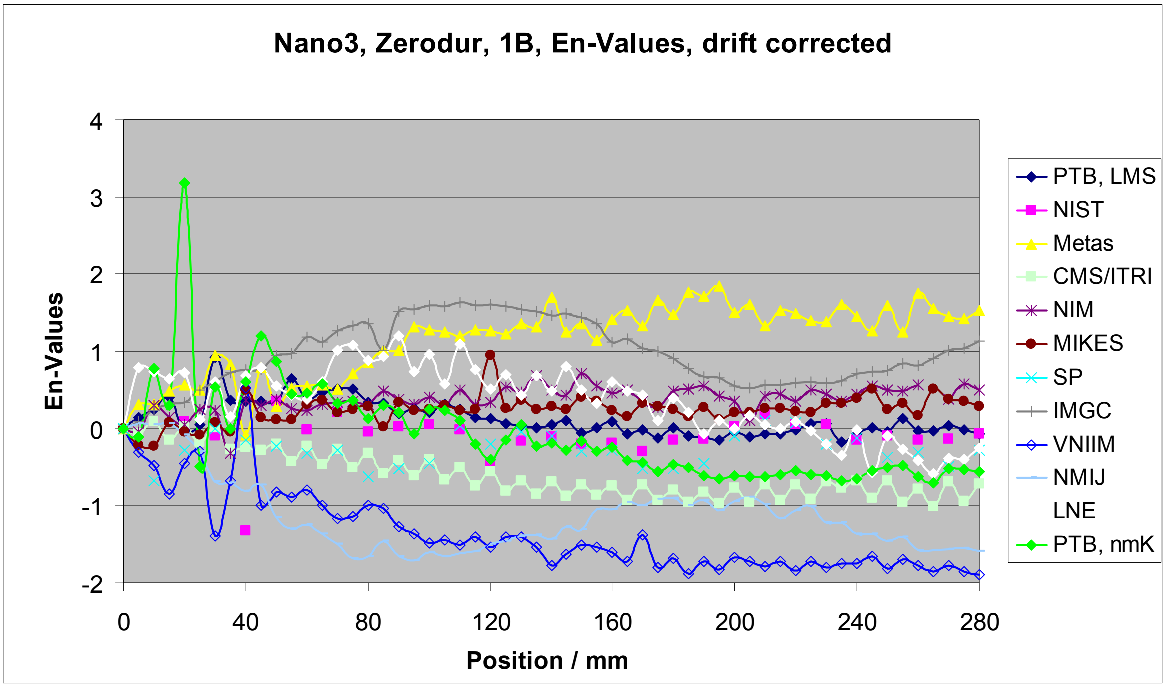

Fig. 30: En-values for results on Zerodur scale, measurand 1B: all participants evaluated.

Figure 31 shows the final distribution of E_n-values after exclusion of the 3 participants.

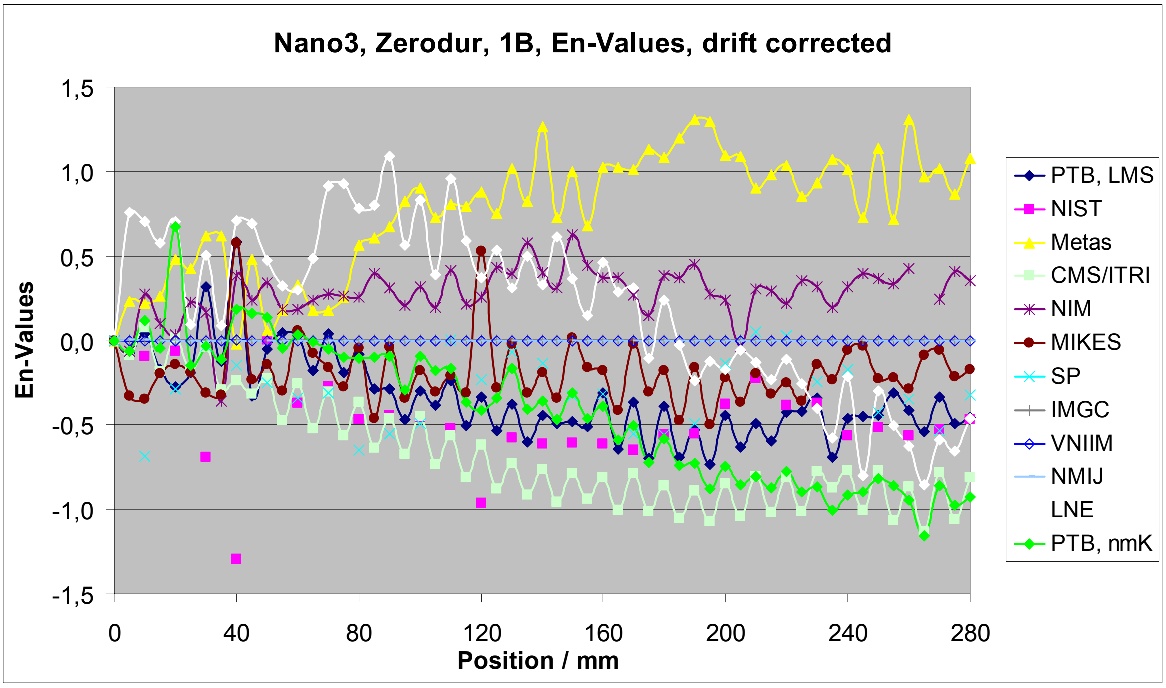

Fig. 31: E_n-values for results on Zerodur scale, measurand 1B: exclusion of results with $|E_n| > 1$.

The remaining set of participants results were used to calculate the weighted mean reference values, as shown in Figure 32.

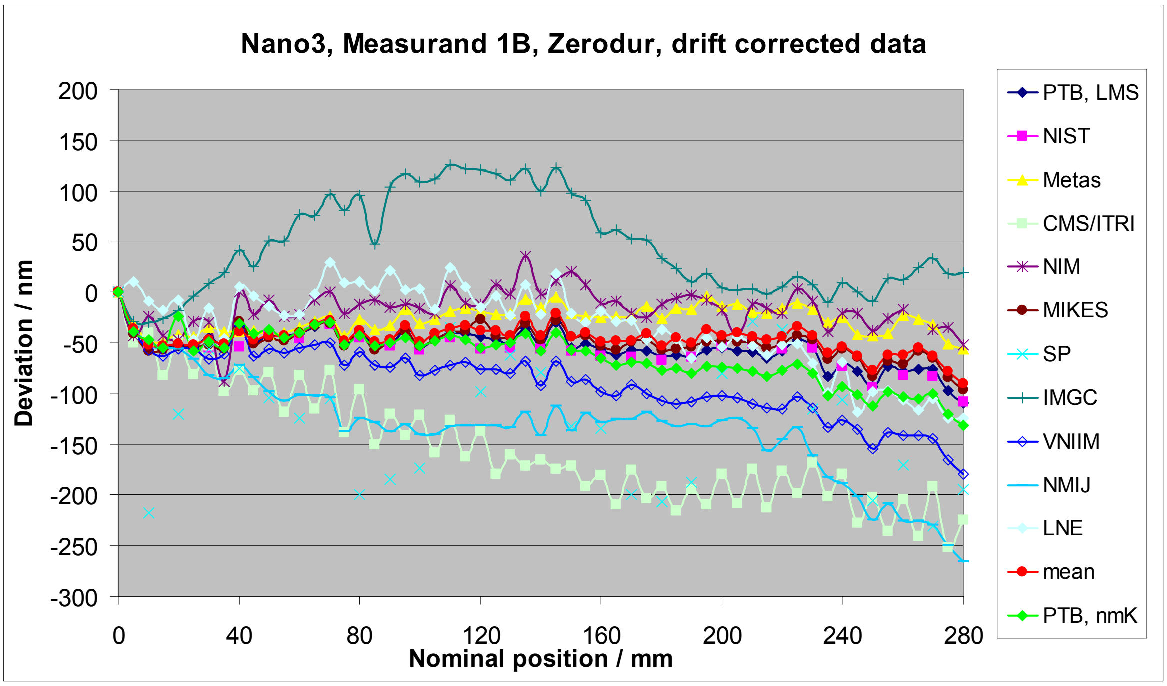

Fig. 32: Results on Zerodur scale, measurand 1B: 280 mm main graduation, 5 mm step. Calculation of weighted mean after exclusion of participants results with $|E_n| > 1$.

Figure 33 gives an enlarged view on the deviations from the reference values.

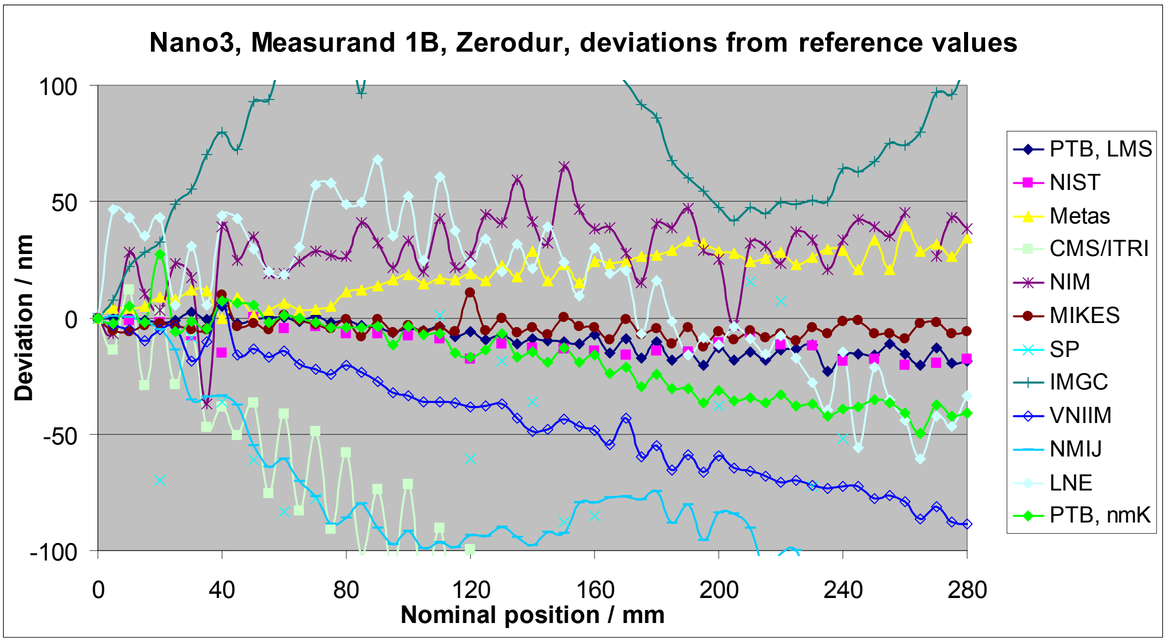

Fig. 33: Results on Zerodur scale, measurand 1B: deviations from reference values.

As before, the resulting slopes of the regression lines were used as the characteristic parameter, describing the different length scale realizations. Table 9 gives an overview of the results on the Zerodur scale.

Table 9: Participants results and slope reference value on Zerodur scale, Task 1B.

Nano3, Zerodur, Task 1B: Deviations from nominal length on main graduation, 5 mm step											
Participant	$u_{c,const}$ / nm	$u_{c,l}$ / 10^{-6}	$\nu_{eff,}$ $_{280}$	$U_{c,const}$ / nm	$U_{c,l}$ / 10^{-6}	*slope* / 10^{-6}	$U_{stat,sl}$ / 10^{-6}	$U_{total,sl}$ / 10^{-6}	$E_{n,}$ $_{slope}$	D_{ir} / 10^{-6}	U_{Dir} / 10^{-6}
PTB, LMS	4,2	0,062	19	9	0,130	-0,149	0,037	0,135	-0,51	-0,08	0,16
NIST	5,2	0,050	7	12	0,118	-0,143	0,053	0,129	-0,48	-0,07	0,15
METAS	10,0	0,034	36	20	0,070	0,040	0,040	0,080	0,99	0,11	0,12
CMS/ITRI	80,0	0,065	73	160	0,130	-0,623	0,072	0,149	*-3,30*	*-0,55*	*0,17*
NIM	51,4	0,047	84	103	0,094	0,010	0,067	0,115	0,58	0,08	0,14
MIKES	8,6	0,041	27	18	0,084	-0,086	0,038	0,092	-0,13	-0,02	0,12
SP	115,0	0,350	56	242	0,735	-0,140	0,288	0,790	-0,09	-0,07	0,79
IMGC, ***	49,5	0,062	43	103	*0,129*	-0,121	0,156	0,202	-0,23	-0,05	0,22
VNIIM, **	3,2	0,044	13	7	*0,100*	-0,384	0,038	0,107	*-2,21*	*-0,31*	*0,14*
NMIJ, *	23,9	0,160	48	41	*0,322*	-0,526	0,081	0,332	*-1,32*	*-0,46*	*0,34*
LNE	31,0	0,060	103	62	0,120	-0,405	0,083	0,146	*-2,03*	*-0,34*	*0,16*
Ref. values			Udrift:	**0,077**	**0,037**	**-0,070**	**0,037**	**0,093**	calculated as weighted mean		
PTB, nmK	20,0	0,008	22	41	0,015	-0,270	0,038	0,041	*-1,96*	*-0,20*	*0,10*
*), **), ***): Participants results excluded from calculation of reference values in subsequent loops											

In contrast to the reference value analysis for the quartz line scale, in Table 9 an additional component for the reference value uncertainty was taken into account to cover the applied drift correction. This contribution was estimated to be $0{,}077\cdot10^{-6}$. The D_{ir} length scale deviations from reference slopes for both line scales are in most cases similar and can thus be used in combination for a correction of the length scale realizations at the NMIs.

Again, it is also of interest to investigate the length-independent contributions within the comparison data. Figure 34 shows the deviations of measured line positions from the reference data set after elimination of observed length scale differences, listed in Table 9.

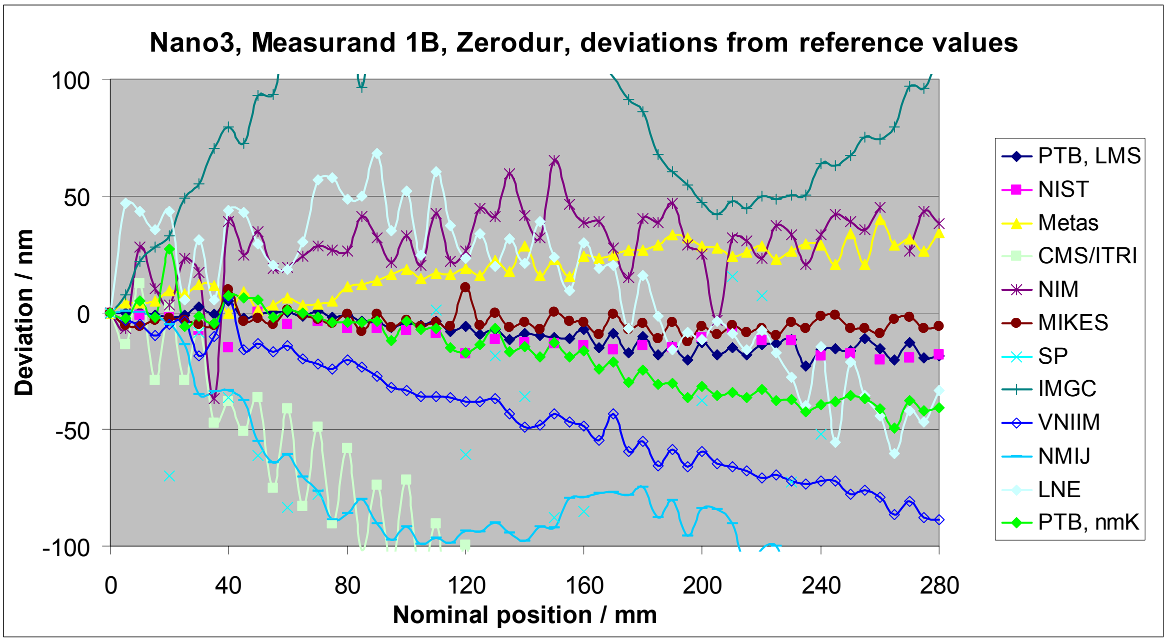

Fig. 34: Results on Zerodur scale, measurand 1B: deviations from reference after linearization.

Table 10: Analysis of participants length-independent results on Zerodur scale, Task 1B.

Nano3, Zerodur, Task 1B: Deviations from reference values after elimination of length scale differences												
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	NIM	MIKES	SP	IMGC	VNIIM	NMIJ	LNE	PTB, nmK
Max. dev. / nm	6,5	11,0	9,8	51,3	34,7	14,7	104,1	67,3	18,3	32,2	38,9	20,9
Min. dev. / nm	-7,1	-9,6	-10,5	-43,4	-58,1	-7,2	-90,5	-100,0	-9,4	-31,6	-59,5	-11,9
2s stddev./nm	5,9	7,9	9,3	53,3	29,5	7,6	112,5	87,9	8,2	41,2	39,4	11,2
Uconst / nm	9,0	12,3	20,0	160,0	103,0	17,7	242,0	103,0	7,0	41,0	62,0	41,0
(2s/U) / %	65%	65%	46%	33%	29%	43%	46%	85%	*117%*	*100%*	64%	27%

Finally, for those laboratories which quoted length-independent measurement uncertainties smaller than 20 nm a direct comparison with the reference data, again after elimination of linearity differences, is shown in Figure 35.

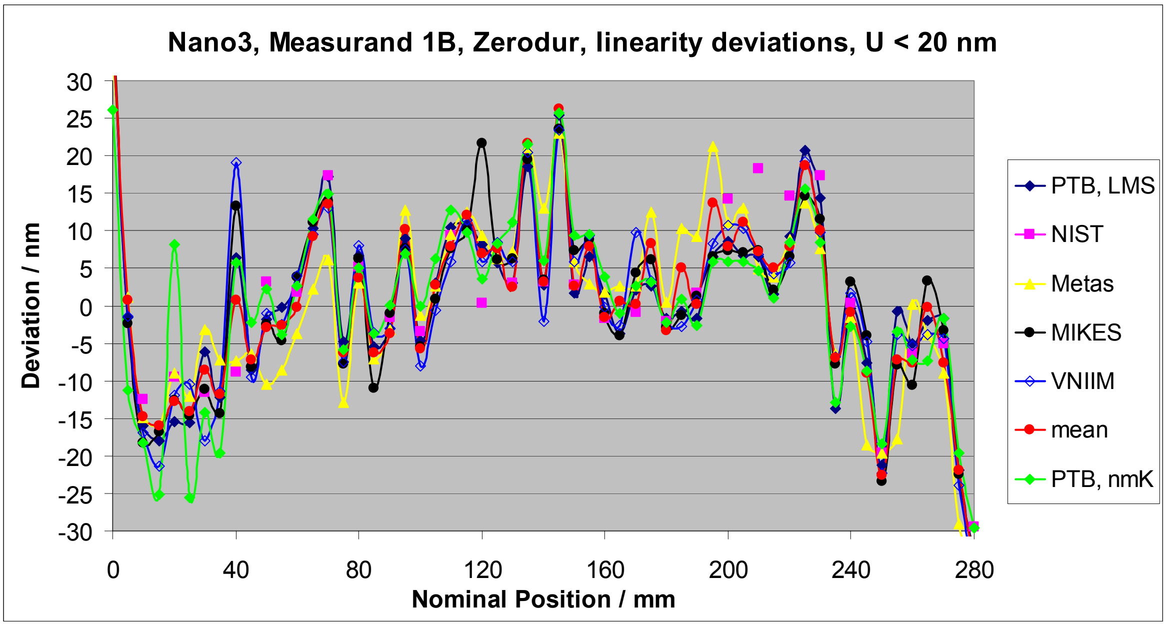

Fig. 35: Results on Zerodur scale, measurand 1B: deviations from linear regression lines, subset.

The linearity deviations of the Zerodur line scale are about 60 nm, whereas the quartz scale shows deviations smaller than 30 nm. This is shown in Figure 36, which displays the calculated reference values and their deviations from linearity for both scales. Annex D contains tables of all the reference data of this comparison.

In general, the standard deviations of the scale adjusted differences from the reference values were slightly smaller for the quartz scale. This could be understood if it is assumed, that the Zerodur scale on average showed an increased level of contamination, e.g. due to increased use compared to the quartz scale. The line edge qualities of both scales however were checked before start of the comparison to be quite similar.

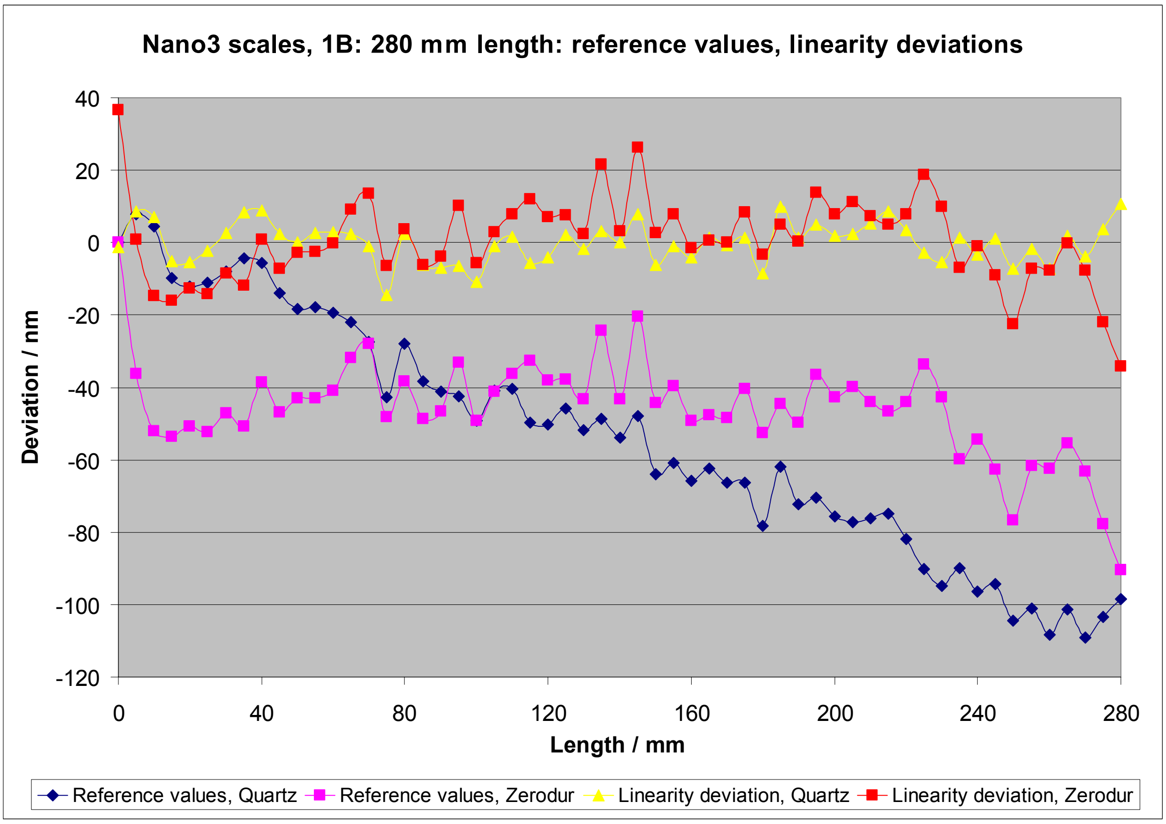

Fig. 36: Reference values and their deviations from linearity for both scales for measurand 1B.

9.3 RESULTS ON LINE SCALES, MEASURAND 1C: 20 MM MAIN GRADUATION, 1MM STEP

The measurements over the first 20 mm of the main graduation with 1 mm step were asked for, because this task resembles calibration tasks on object micrometer scales with typical scale length up to 10 mm or 20 mm, which sometimes also are performed on the line scale comparators. As before, the results on the **quartz scale** are presented first.

For this measurand 1C however, no analysis of the length-dependent differences is made, because the measurement uncertainties are already dominated by the length-independent contributions. Figure 37 shows all participants results for task 1C. With the exception of only a few outlying data points, the E_n-values were all smaller than one, thus all data sets were used for calculation of reference data. In Figure 38 the linearity deviations of the participants and the reference data set are plotted for a subset of results which show very small deviations from the reference values. Table 10 finally provides an overview of the statistical analysis of these linearity deviations.

Table 10: Analysis of participants length-independent results on quartz scale, Task 1C.

Nano3, Quartz, Task 1C: Deviations from reference values after elimination of length scale differences											
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	NIM	MIKES	SP	IMGC	VNIIM	NMIJ	LNE	PTB, nmK
Max. dev. / nm	2.4	3.2	4.0	44.7	7.6	2.8	103.9	12.6	10.2	25.5	19.0	3.3
Min. dev. / nm	-4.0	-3.5	-6.9	-49.1	-7.6	-3.4	-33.2	-14.1	-6.3	-19.0	-21.9	-6.0
2s stddev./nm	2.9	2.7	6.0	59.7	8.8	3.3	63.2	12.6	6.5	18.2	21.0	4.8
Uconst / nm	9.0	4.7	20.0	164.0	103.0	17.7	242.0	94.0	7.0	42.0	62.0	41.0
(2s/U) / %	32%	57%	30%	36%	9%	19%	26%	13%	93%	43%	34%	12%

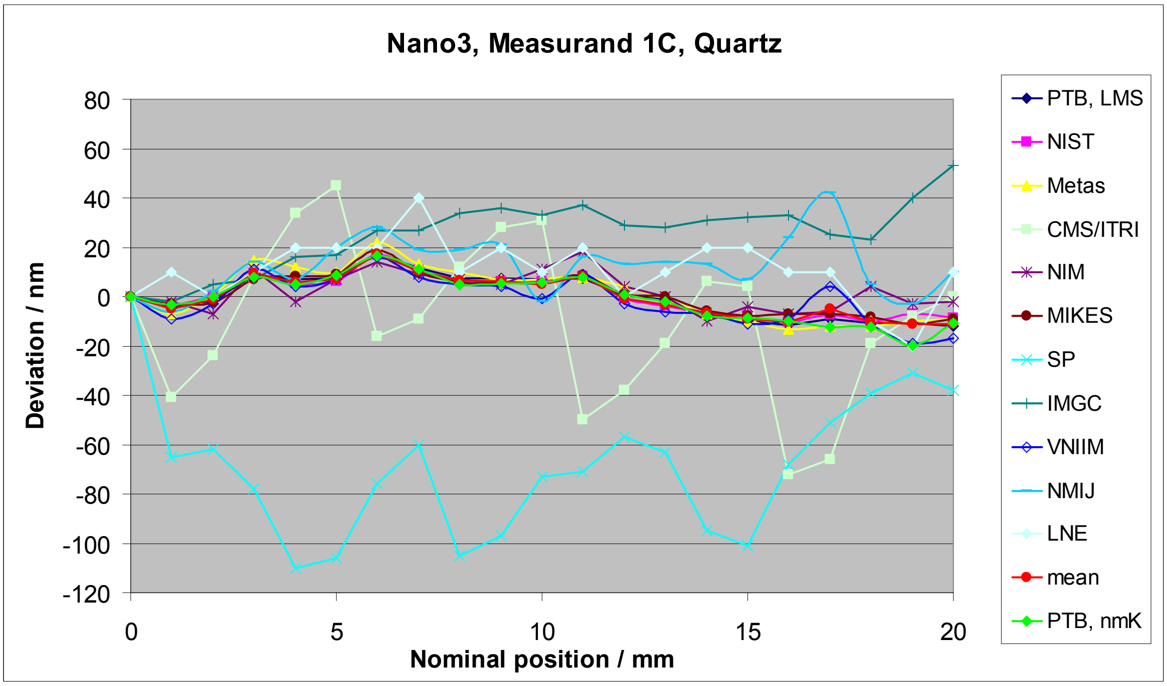

Fig. 37: Results on quartz scale, measurand 1C: First 20 mm on main graduation, 1 mm step. All values used for calculation of weighted mean.

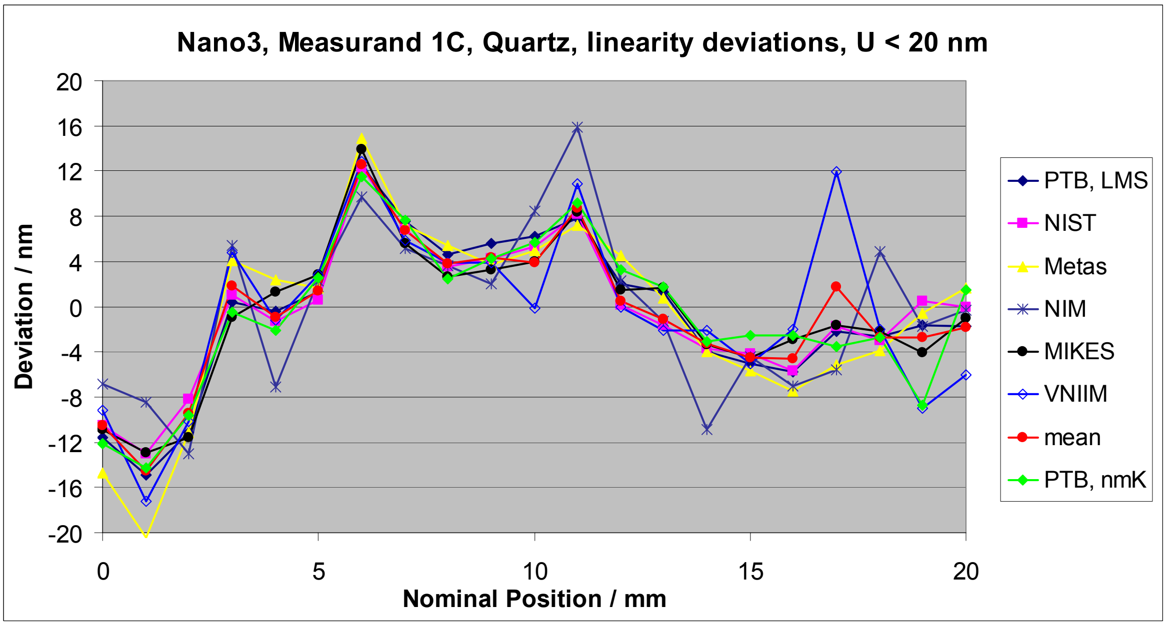

Fig. 38: Results on quartz scale, measurand 1C: Deviations from linearity for subset of results.

The results for task 1C on the **Zerodur scale** are presented in Figures 39 and 40 in a similar way as for the quartz standard (although the drift correction for the 20 mm length yields a maximum contribution of only 3 nm, it was applied to the measurement data). For the Zerodur scale too, all measurement data had E_n-values smaller than one. Table 11 gives an overview of the statistical analysis of the linearity deviations.

In general it can be stated from the results of task 1C, that most of the participants had over-estimated their length-independent uncertainty contributions.

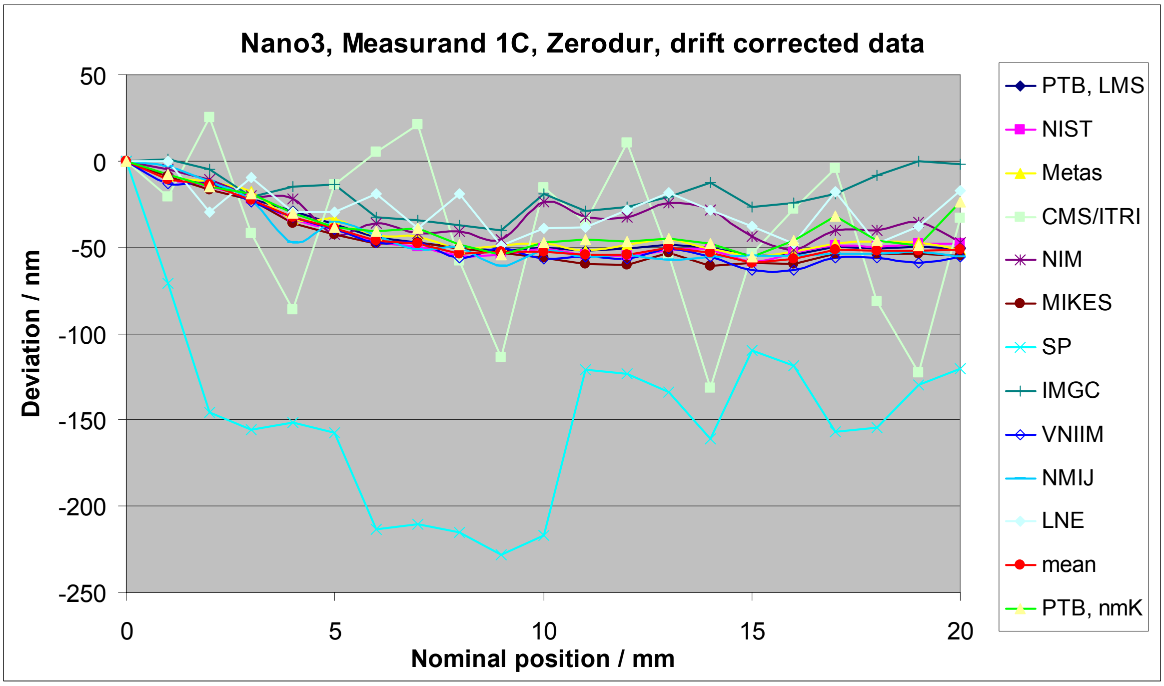

Fig. 39: Results on Zerodur scale, measurand 1C: First 20 mm on main graduation, 1 mm step. All measurement values used for calculation of weighted mean reference values.

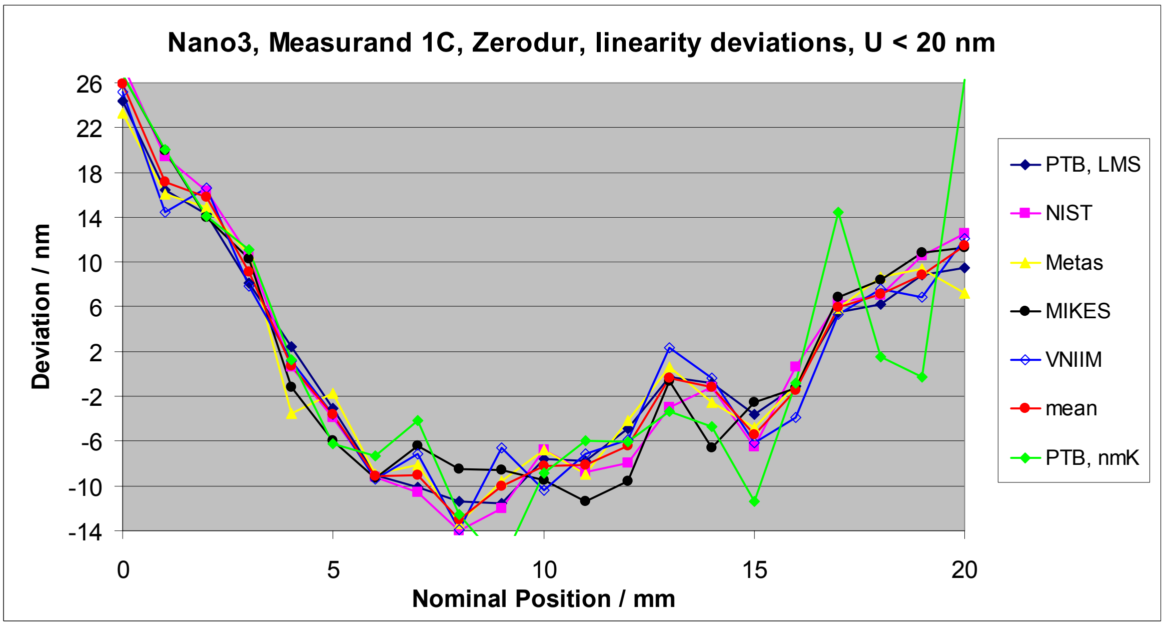

Fig. 40: Results on Zerodur scale, measurand 1C: Deviations from linearity for subset of results.

Table 11: Analysis of participants length-independent results on Zerodur scale, Task 1C.

Nano3, Zerodur, Task 1C: Deviations from reference values after elimination of length scale differences												
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	NIM	MIKES	SP	IMGC	VNIIM	NMIJ	LNE	PTB, nmK
Max. dev. / nm	1,9	2,3	2,3	62,6	17,2	4,5	143,2	10,8	3,4	7,6	21,1	14,8
Min. dev. / nm	-2,0	-2,7	-4,3	-79,1	-13,2	-5,4	-61,4	-10,4	-2,7	-14,7	-23,5	-9,2
2s stddev./nm	2,3	2,8	3,6	86,4	16,4	4,8	95,2	12,1	3,2	9,7	22,7	10,6
Uconst / nm	9,0	6,6	20,0	161,0	103,0	17,7	242,0	84,0	7,0	41,0	62,0	41,0
(2s/U) / %	26%	42%	18%	54%	16%	27%	39%	14%	46%	24%	37%	26%

9.4 RESULTS ON LINE SCALES, MEASURAND 2D: 4,6 MM AUX. GRADUATION, 0,1 MM STEP

At some of the comparators involved here, a special fine adjustment stage is used for line edge positioning and edge detection. It was therefore decided, to have also finer graduations measured by the participants. However, for the tasks 2D and 2E not all participants were able to provide measurement data. At first the results on the **quartz scale** are presented in a similar way as in section 9.3.

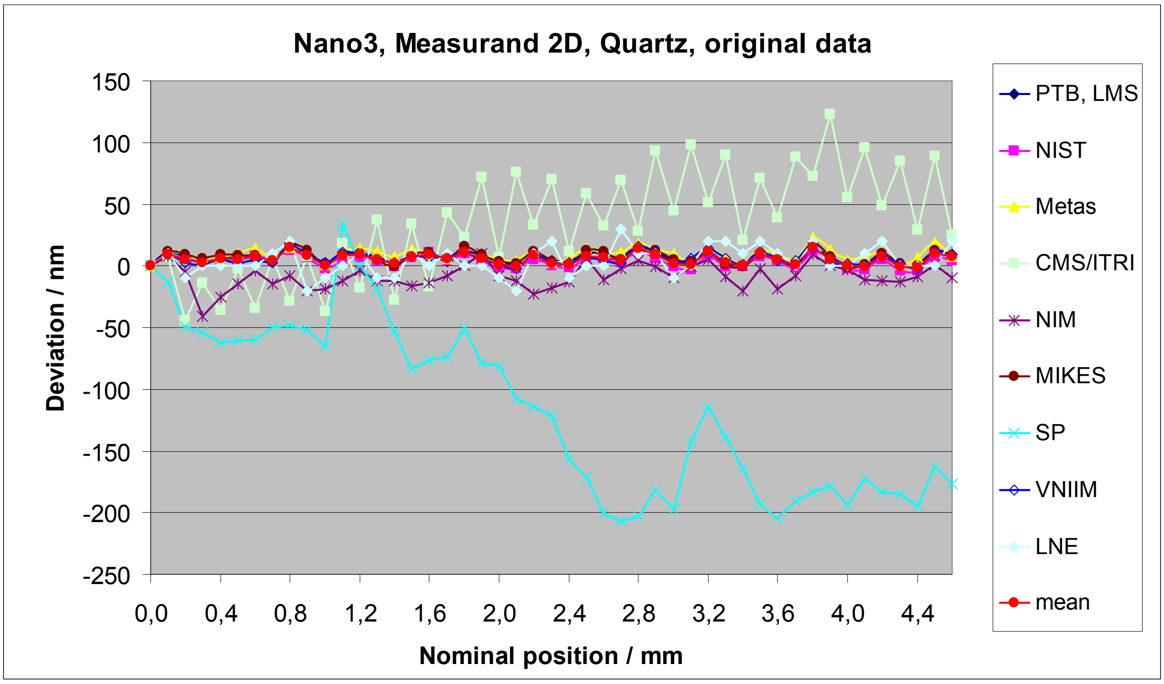

Fig. 41: Results on quartz scale, measurand 2D: 4,6 mm on aux. graduation, 0,1 mm step. All measurement values used for calculation of weighted mean reference values.

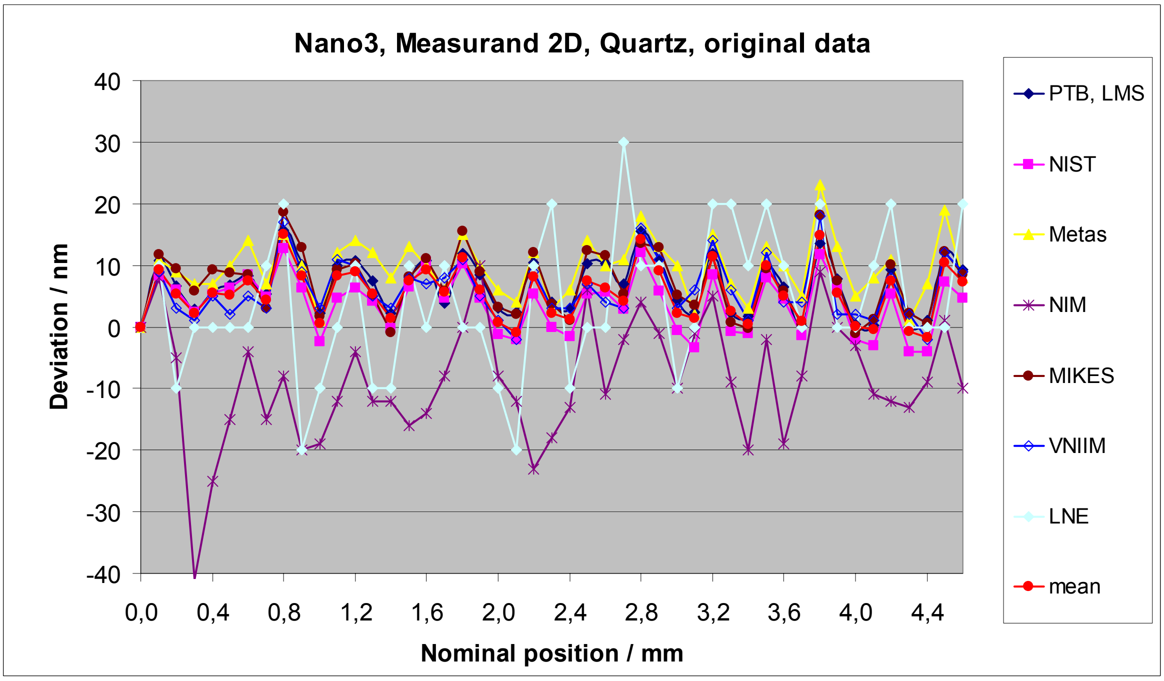

Fig. 42: Results on quartz scale, measurand 2D: 4,6 mm on aux. graduation, 0,1 mm step, subset.

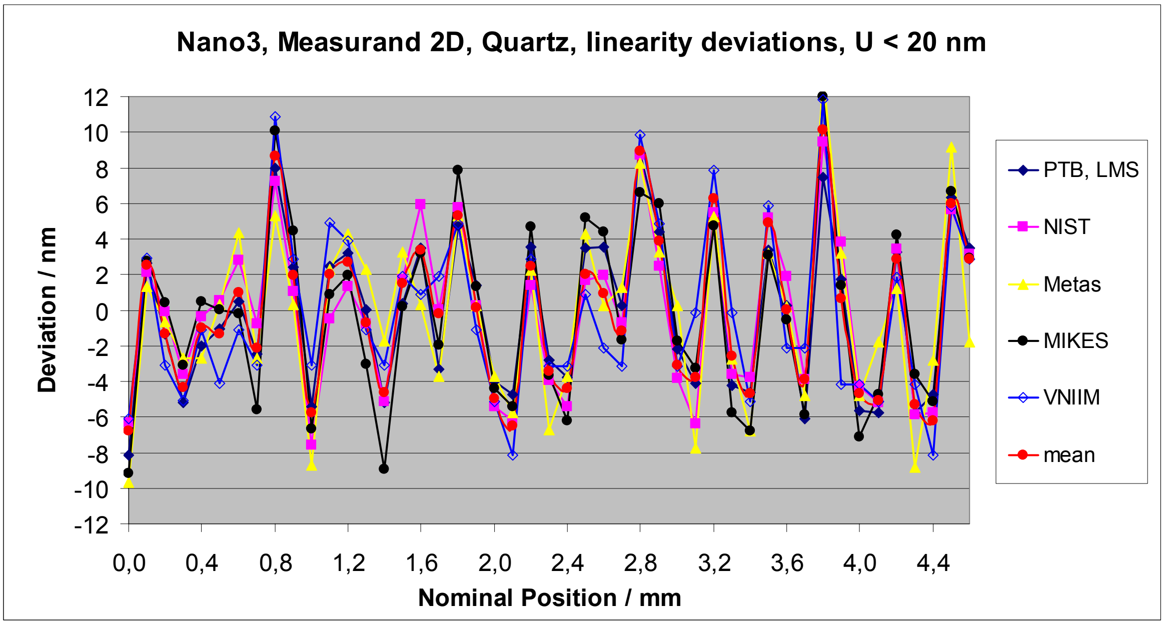

Fig. 43: Results on quartz scale, measurand 2D: Deviations from linearity for subset of results.

Table 12: Analysis of participants length-independent results on quartz scale, Task 2D.

Nano3, Quartz, Task 2D: Deviations from reference values after elimination of length scale differences									
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	NIM	MIKES	SP	VNIIM	LNE
Max. dev. / nm	2,6	3,2	3,4	53,7	20,2	3,4	96,6	3,6	26,1
Min. dev. / nm	-3,1	-2,6	-4,7	-65,5	-23,8	-4,4	-74,4	-4,8	-22,2
2s stddev./nm	2,3	2,4	4,6	58,8	17,5	3,7	69,7	3,5	19,2
Uconst / nm	9,0	6,4	20,0	161,0	103,0	17,7	242,0	7,0	62,0
(2s/U) / %	25%	37%	23%	36%	17%	21%	29%	50%	31%

The results for task 2D on the **Zerodur scale** are described in the following. Again, all participants data were used for calculation of the weighted mean reference value.

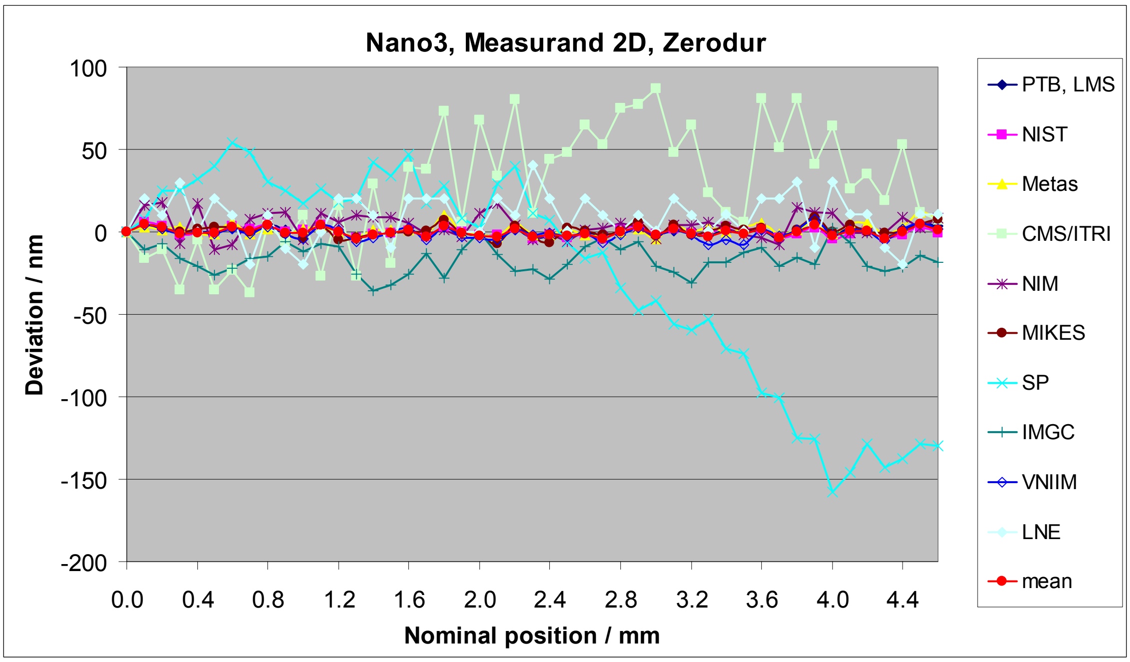

Fig. 44: Results on Zerodur scale, measurand 2D: 4,6 mm on aux. graduation, 0,1 mm step.

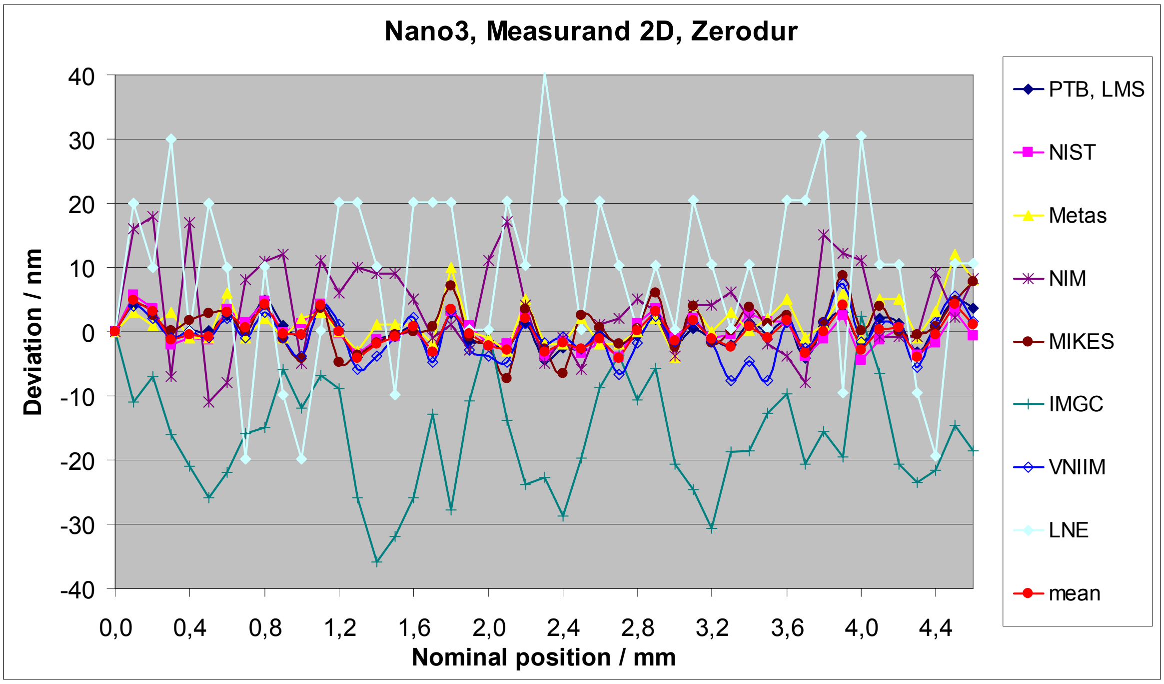

Fig. 45: Results on Zerodur scale, measurand 2D: 4,6 mm on aux. graduation, 0,1 mm step, subset.

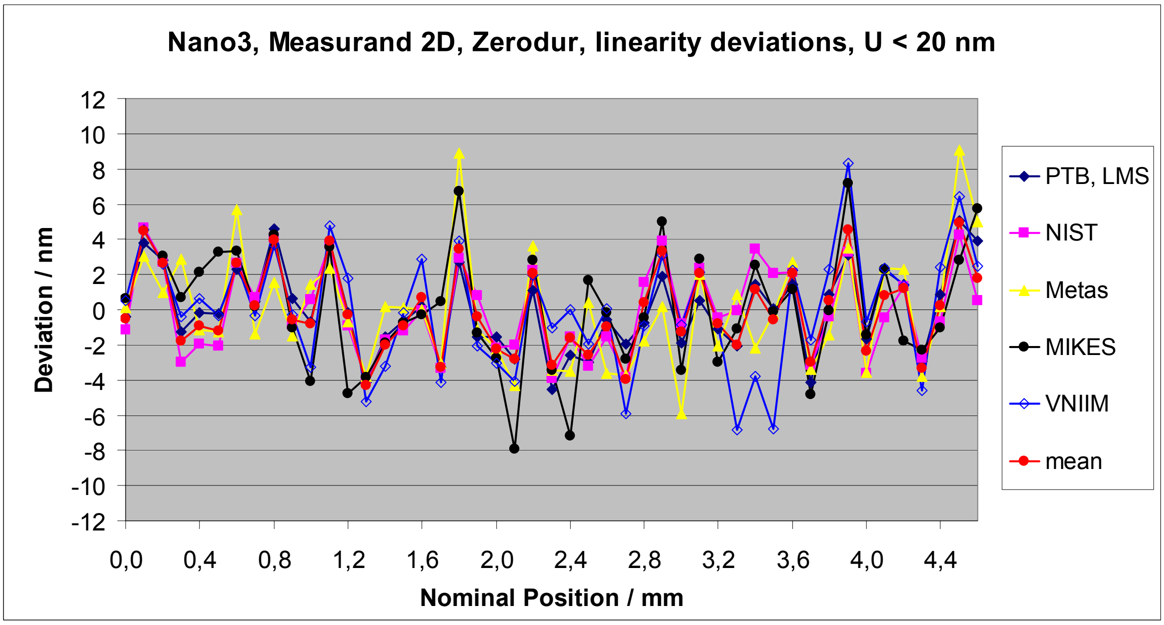

Fig. 46: Results on Zerodur scale, measurand 2D: Deviations from linearity for subset of results.

Table 13: Analysis of participants length-independent results on quartz scale, Task 2D.

Nano3, Quartz, Task 2D: Deviations from reference values after elimination of length scale differences										
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	NIM	MIKES	SP	IMGC	VNIIM	LNE
Max. dev. / nm	2,1	2,6	5,4	53,3	15,7	4,5	58,6	21,3	3,8	34,0
Min. dev. / nm	-1,6	-1,3	-4,7	-56,5	-16,0	-5,6	-78,2	-17,0	-6,2	-29,7
2s stddev./nm	1,7	1,8	4,3	59,5	14,5	4,6	60,2	18,1	3,8	28,3
Uconst / nm	9,0	4,7	20,0	161,0	103,0	17,7	242,0	74,0	7,0	62,0
(2s/U) / %	19%	39%	21%	37%	14%	26%	25%	24%	54%	46%

9.5 RESULTS ON LINE SCALES, MEASURAND 2E: 0,46 MM AUX. GRAD., 0,01 MM STEP

At first the results for the measurand 2E on the **quartz scale** are presented in a similar way as in section 9.4.

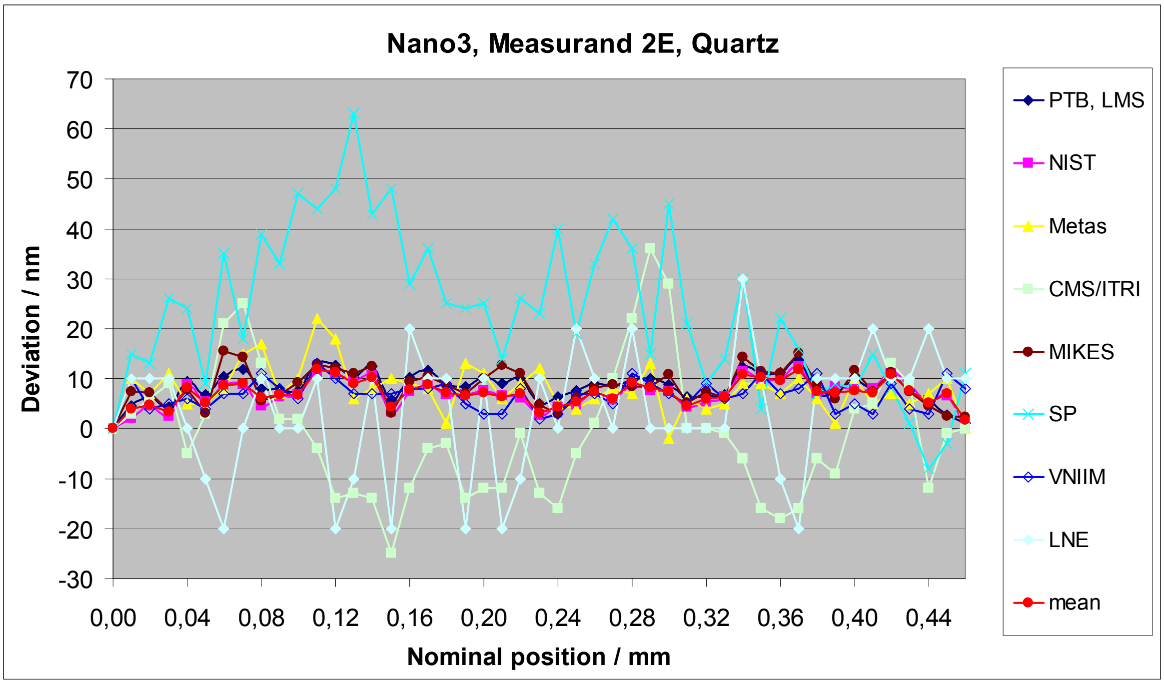

Fig. 47: Results on quartz scale, measurand 2E: 0,46 mm on aux. graduation, 0,01 mm step. All measurement values used for calculation of weighted mean reference values.

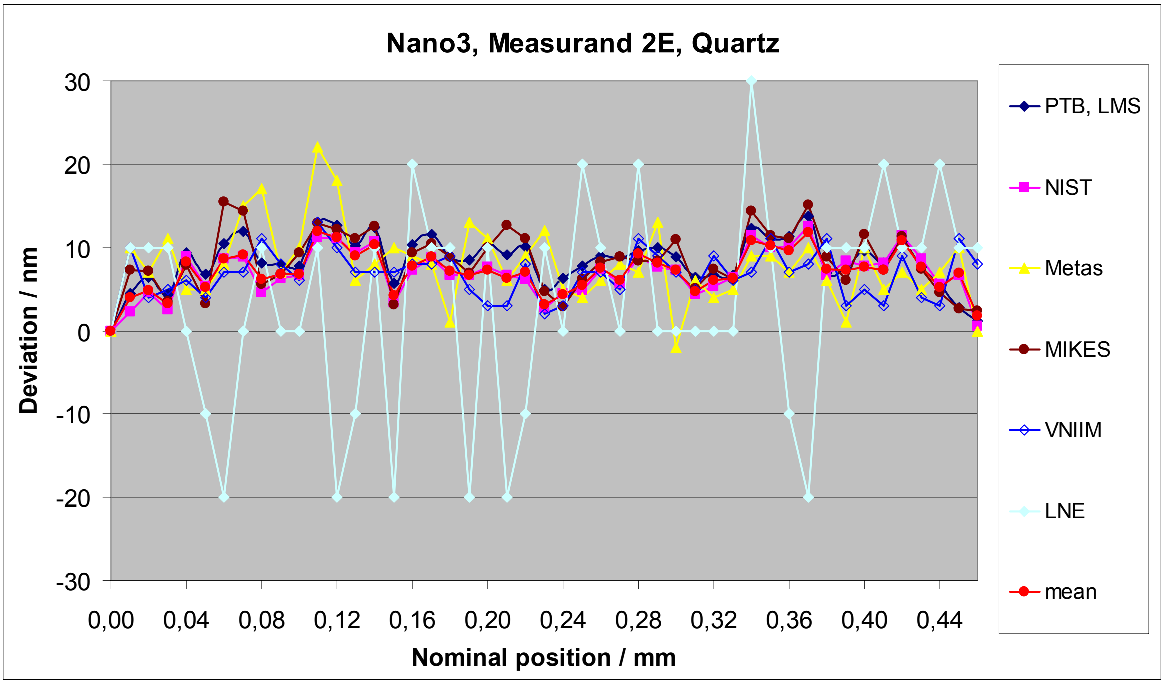

Fig. 48: Results on quartz scale, measurand 2E: 0,46 mm on aux. graduation, 0,01 mm step, subset.

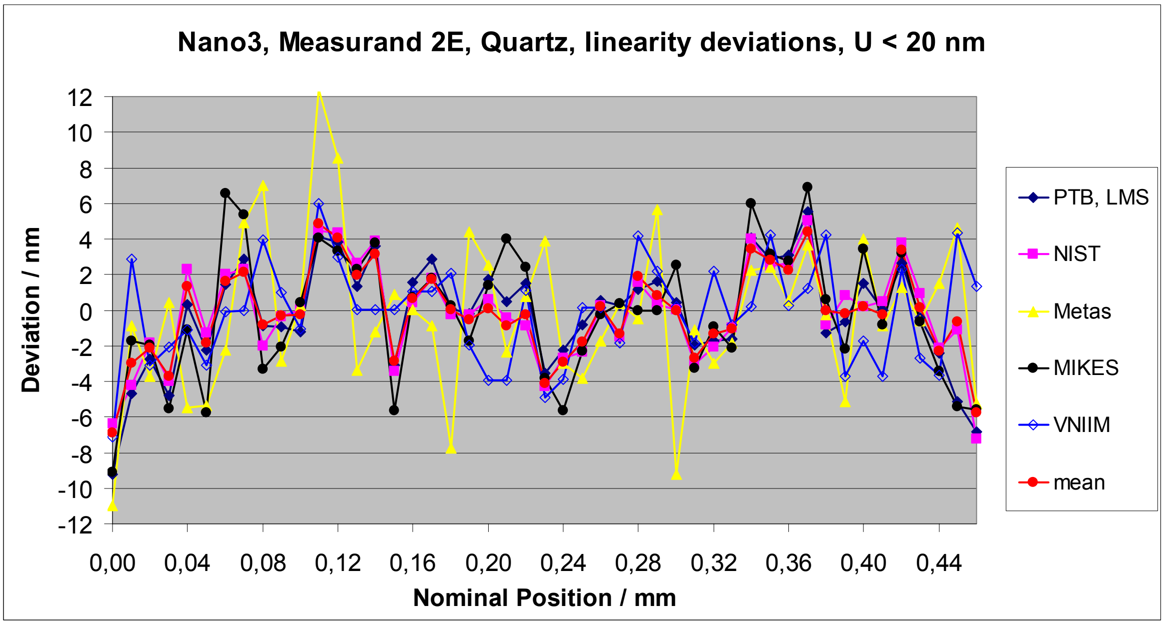

Fig. 49: Results on quartz scale, measurand 2E: Deviations from linearity for subset of results.

Table 13: Analysis of participants length-independent results on quartz scale, Task 2E.

Nano3, Quartz, Task 2E: Deviations from reference values after elimination of length scale differences								
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	MIKES	SP	VNIIM	LNE
Max. dev. / nm	1,7	1,0	8,0	36,4	4,9	30,6	7,1	20,4
Min. dev. / nm	-4,5	-1,5	-9,2	-21,8	-4,8	-31,5	-4,0	-31,4
2s stddev./nm	2,3	1,1	7,9	26,5	4,1	26,8	5,3	24,8
Uconst / nm	9,0	3,3	20,0	161,0	17,7	242,0	7,0	62,0
(2s/U) / %	25%	35%	39%	16%	23%	11%	76%	40%

The results for task 2E on the **Zerodur scale** are described in the following. Again, all participants data were used for calculation of the weighted mean reference value.

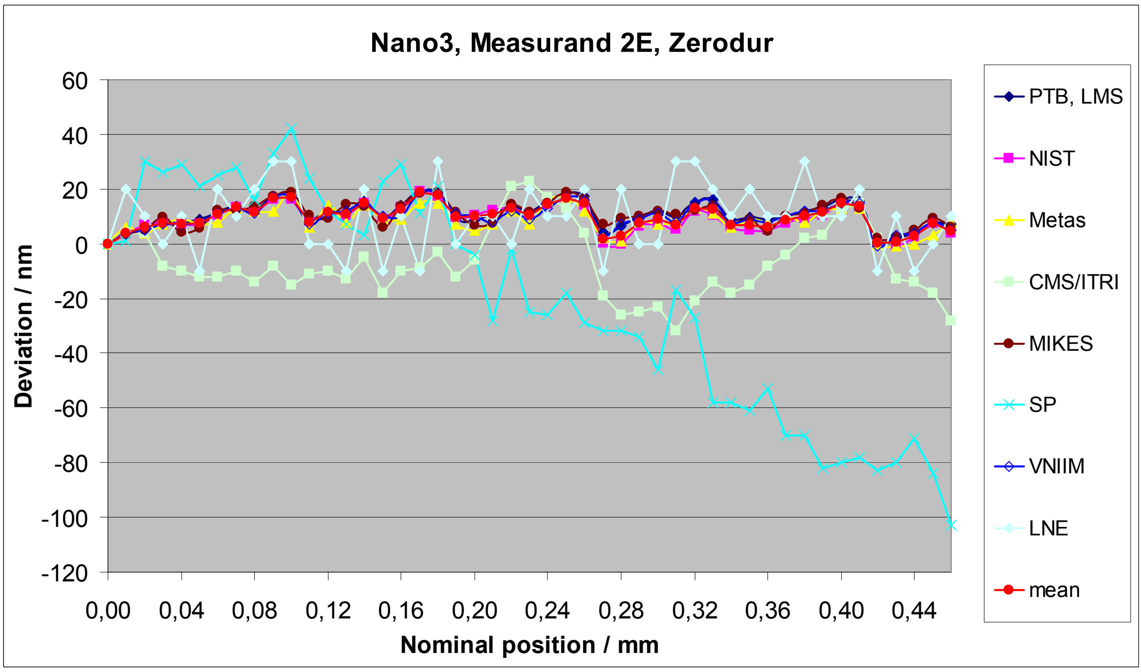

Fig. 50: Results on Zerodur scale, measurand 2E: 0,46 mm on aux. graduation, 0,01 mm step.

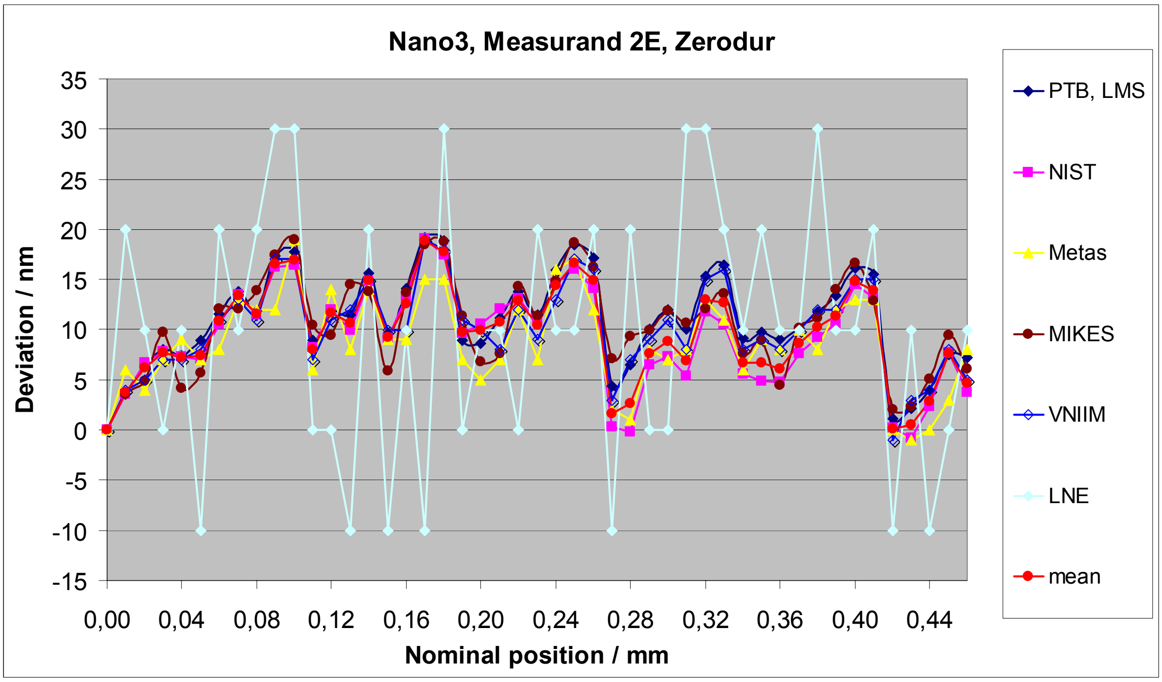

Fig. 51: Results on Zerodur scale, measurand 2E: 0,46 mm on aux. graduation, 0,01 mm step, subset.

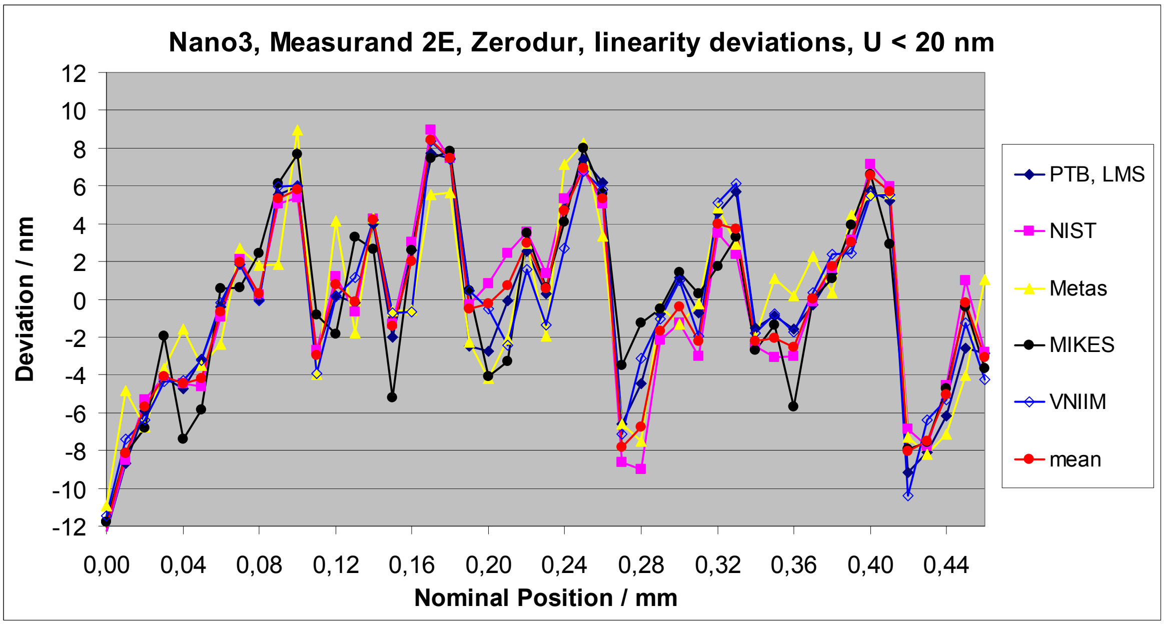

Fig. 52: Results on Zerodur scale, measurand 2E: Deviations from linearity for subset of results.

Table 14: Analysis of participants length-independent results on Zerodur scale, Task 2E.

Nano3, Zerodur, Task 2E: Deviations from reference values after elimination of length scale differences								
Participant	PTB, LMS	NIST	METAS	CMS/ITRI	MIKES	SP	VNIIM	LNE
Max. dev. / nm	2,3	1,7	4,1	29,7	5,5	28,3	3,6	22,3
Min. dev. / nm	-2,5	-2,3	-3,9	-22,1	-4,0	-35,6	-3,1	-28,5
2s stddev./nm	2,0	1,4	4,2	24,5	4,1	26,8	2,5	23,1
Uconst / nm	9,0	4,3	20,0	161,0	17,7	242,0	7,0	62,0
(2s/U) / %	22%	33%	21%	15%	23%	11%	36%	37%

10 DISCUSSIONS, CONCLUSIONS AND REMARKS

The Nano3 comparison was intended to document current capabilities of participating NMIs to carry out line scale calibrations on high quality graduated scales of 300 mm length made of low thermal expansion substrates. The standards used for the comparison were designed in close cooperation between the pilot laboratory and the Dr. Johannes Heidenhain GmbH, Traunreut in Germany. Following production of and preliminary investigations on test scales, the scales used for the Nano3 comparison were manufactured in the end of 1999 (Zerodur) and in the beginning of 2000 (quartz).

The comparison started in May 2000 and the last participant performed the calibrations in April 2002. From 13 participating NMIs of 4 different RMOs, 11 provided measurement reports on their data and 2 institutes decided to officially withdraw their participation after measurements of the scales were carried out. This final report however, is published one year after the official end of the comparison, because the pilot laboratory decided to include first measurements on the circulated standards by means of its newly developed vacuum line scale comparator (measurements performed with PTBs nanometer comparator in February and March 2003) and because the Zerodur standard showed a long-term relaxation behaviour, which could be described with better reliability over the 3 years period.

In addition to the two line scale standards used for the comparison, two additional control standards from every substrate material were manufactured with identical graduation layout but different length scale realizations. Furthermore, for independent calibrations of material properties, namely the thermal expansion and the length compressibility as well as investigations concerning the long-term dimensional stability, two long gauge blocks were manufactured from each of the substrate material discs. On the Zerodur gauge blocks, the measurements performed in PTBs precision interferometer revealed a mid-term thermal hysteresis behaviour after temperature changes of 10 °C with typical time constants of about 3 days. These hysteresis effects which could be induced e.g. by temperature changes during transportation could superimpose on the known long-term dimensional contraction of Zerodur and had to be taken into account for analysis of the comparison results.

The circulated Zerodur line scale standard showed a small relative length contraction of about $(-7 \pm 4)\cdot 10^{-8}$/a over the period of 3 years. This observed length reduction was confirmed by additional measurements on the two control line standards made from the same substrate material. Recalibrations of the lengths of the gauge block samples from the same material independently confirmed the length contraction rate ($-6.4 \cdot 10^{-8}$/a). A linear model of the small drift of the Zerodur standard could successfully be applied to the results of the participating institutes (a stepwise correction showed comparable results). The drift corrected data finally were in good agreement to the calibration results on the quartz scale, which proved to be stable over the time of the circulation.

Different types of instrumentation were used for the calibrations, namely traditional line scale comparators which were developed in the past primarily for calibrations of meter prototypes as well as newly developed comparators for measurement on 1D and also 2D objects with fine graduations. The spread of evaluated measurement uncertainties therefore reflects the different capabilities of instrumentation. Thus, calculation of the reference values was based on the weighted mean of all results, after exclusion of values with $|E_n|>1$.

For the most important measurand of this comparison, namely the position deviations of the line structures on the 280 mm main graduation, 3 results out of the 11 data sets provided had to be excluded by application of the E_n-criterion for the quartz and Zerodur scale respectively. Thus, the reference values are based on 8 participants' data sets only. For the traditional metrology field of line scale calibrations, a better agreement of the results would have been expected. However, it has to be taken into account, that some new or recently upgraded instrumentation was used in this comparison and that some participants might have underestimated especially their length-dependent uncertainty contributions on the line scales used in Nano3. On the other hand, the pilot laboratory is convinced, that most of the observed deviations can be properly analysed by the participants on the basis of this report and appropriate correction actions will be made to improve the agreement of line scale calibrations in the future.

Most of the participants within Nano3 reported smaller measurement uncertainties than they quoted for the CMC tables in the MRA data base for line scale calibrations. Possible explanations for these differences might be, that the CMC entries are specified e.g. for steel scales which can be calibrated with increased uncertainties only or for larger measurement ranges. On the other side, 5 out of 13 participants did not yet specify a line scale calibration service in the CMC tables.

Thus the importance and meaning of the Nano3 results for the CMC line scale entries and the comparability of world-wide line scale measurements performed by the NMIs will have to be further analyzed. For this task, meanwhile a discussion group (DG9) was established within the CCL Working Group on Dimensional Metrology (WGDM). Some of the questions to be answered by this group are: What is the relation between CMC entries for line scales and Nano3 results? How can the Nano3 results be transferred to other NMIs within the different Regional Metrology Organizations (RMO)[14]? Will a future comparison be necessary, which then will be started as a key comparison from the beginning? Will quartz scales which proved to show better stability compared to Zerodur be used for such a comparison? Would this comparison then cover steel scales and a larger measurement range too? Will it be possible or necessary in the future to include also length encoder systems as circulated standards?

The last question indeed might be important for the NMIs, because recently examples were given[15], that at an industrial level, two laboratories were able to achieve an agreement of their measurements on a 270 mm length encoder system by $0{,}1\cdot10^{-6}$. In this Nano3 comparison on 280 mm line scales, all the participants results on the quartz scale showed a 1s-standard deviation of their length-dependent contributions of $0{,}46\cdot10^{-6}$ and for those participants with $|E_n| < 1$, a 1s-standard deviation of $0{,}11\cdot10^{-6}$ resulted. On the Zerodur scale, the corresponding standard deviations were found to be $0{,}21\cdot10^{-6}$ and $0{,}06\cdot10^{-6}$.

11 ACKNOWLEDGEMENT

The pilot laboratory would like to thank all involved colleagues in the participating laboratories for their good cooperation in this extensive measurement comparison. This of course also holds for all colleagues involved at PTB, especially those who provided the data on the gauge block samples and those who had worked with the AIK and who have since retired.
However, without the special interest and generous support of the manufacturer of the line

[14] The pilot laboratory was already contacted by some NMIs which are interested in a follow-up line scale comparison or at least a bilateral comparison.
[15] W. Israel et al: An international length comparison at an industrial level using a photoelectric incremental encoder as transfer standard, Precision Engineering, 27 (2003) 151-156

scales, the Dr. Johannes Heidenhain GmbH, this comparison could never have been started and conducted. Therefore, we would in particular like to thank all persons involved in preparation and manufacturing process of the line scale standards at Heidenhain.

Physikalisch-Technische Bundesanstalt

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According to the rules of CCL key comparisons

NANO 3

LINE SCALE STANDARDS

FINAL REPORT

ANNEX A

Original time schedule of Nano3 comparison

Braunschweig, August 29, 2003

Original time schedule of Nano3 comparison

(excerpt from Nano3 technical protocol from May 2000)

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 **five weeks for calibration, including transportation**. 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. It guarantees that the standards arrive in the country of the next participant according to the time schedule. If for some reasons, the measurement facility is not ready or customs clearance takes too much time in a country, the laboratory has to contact the coordinator immediately and – according to the arrangement made - eventually to send the standards directly to the next participant before finishing the measurements or even without doing any measurements.

Region	**Laboratory**	**COUNTRY**	**Dates (5 weeks/participant)**
	PTB (pilot)	DE	April 2000
NORAMET	NIST	USA	15 May 2000 - 19 June 2000
	NRC	CA	19 June 2000 - 24 July 2000
	PTB (pilot)	DE	24 July 2000 - 28 Aug. 2000
EUROMET	OFMET	CH	28 Aug. 2000 - 2 Oct. 2000
APMP	CMS	TW	2 Oct. 2000 - 6 Nov. 2000
	NIM	CN	13 Nov. 2000 - 18 Dec. 2000
	NRLM	JP	18 Dec. 2000 - 29 Jan. 2001
	KRISS	KR	29 Jan. 2001 - 5 March 2001
	PTB (pilot)	DE	5 March 2001 - 2 April 2001
COOMET	VNIIM	RU	2 April 2001 - 7 May 2001
EUROMET	MIKES	FI	7 May 2001 - 11 June 2001
	SP	SE	11 June 2001 -16 July 2001
	NPL	UK	16 July 2001 - 20 Aug. 2001
	IMGC	IT	20 Aug. 2001 - 24 Sep. 2001
	LNE	FR	24 Sep. 2001 - 29 Oct. 2001
	PTB (pilot)	DE	29 October 2001

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ANNEX B

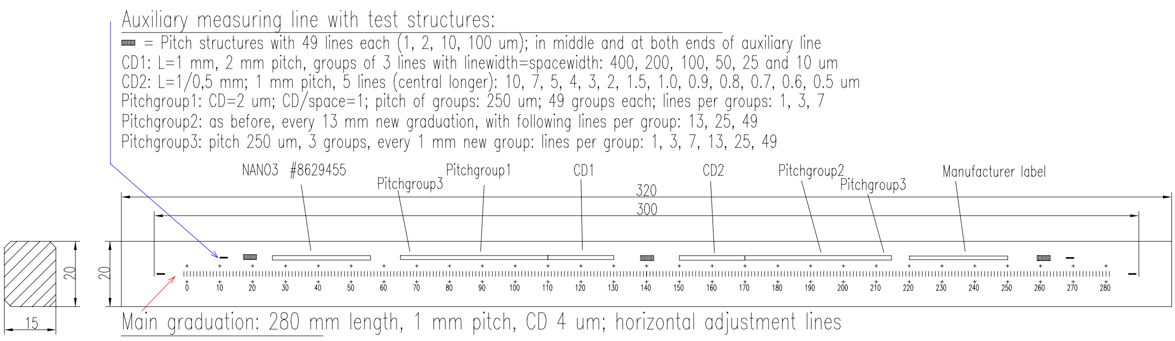
Detailed description of line scales

Braunschweig, August 29, 2003

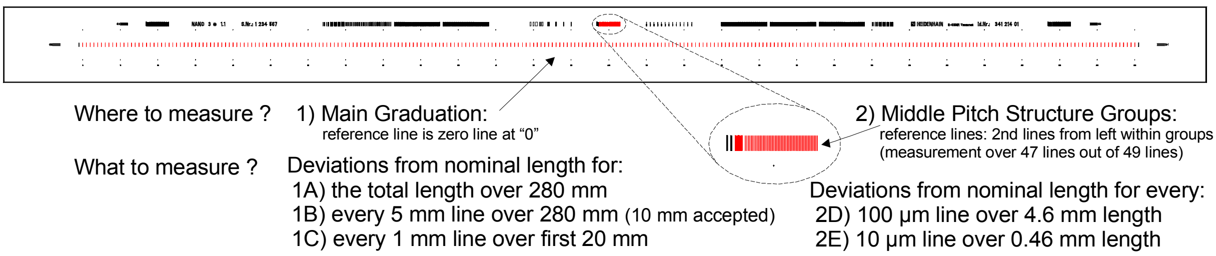
Detailed description of line scales
(taken from Nano3 technical protocol from May 2000)

Line scale layout

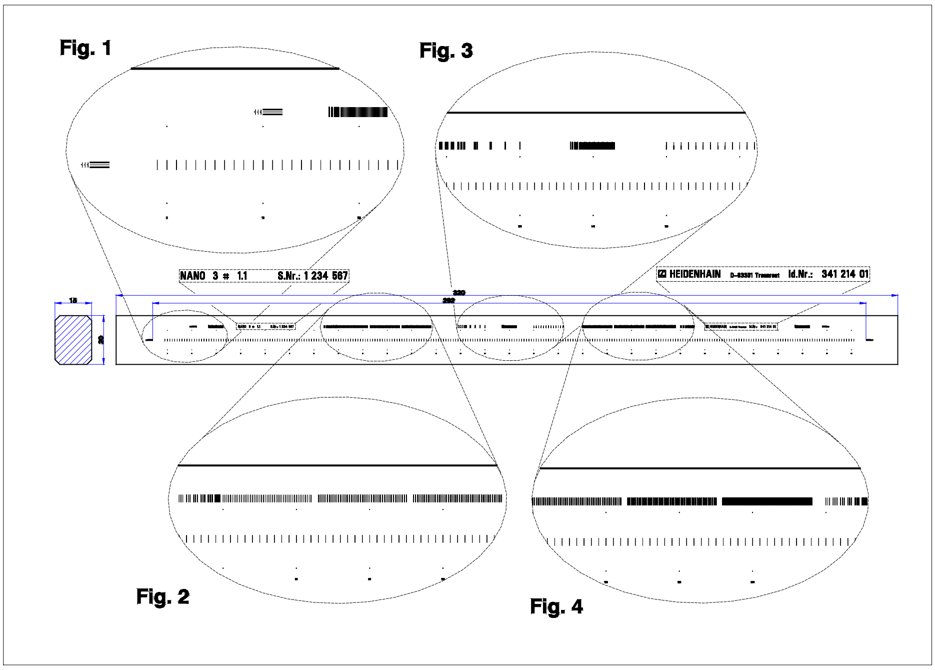
Overview:



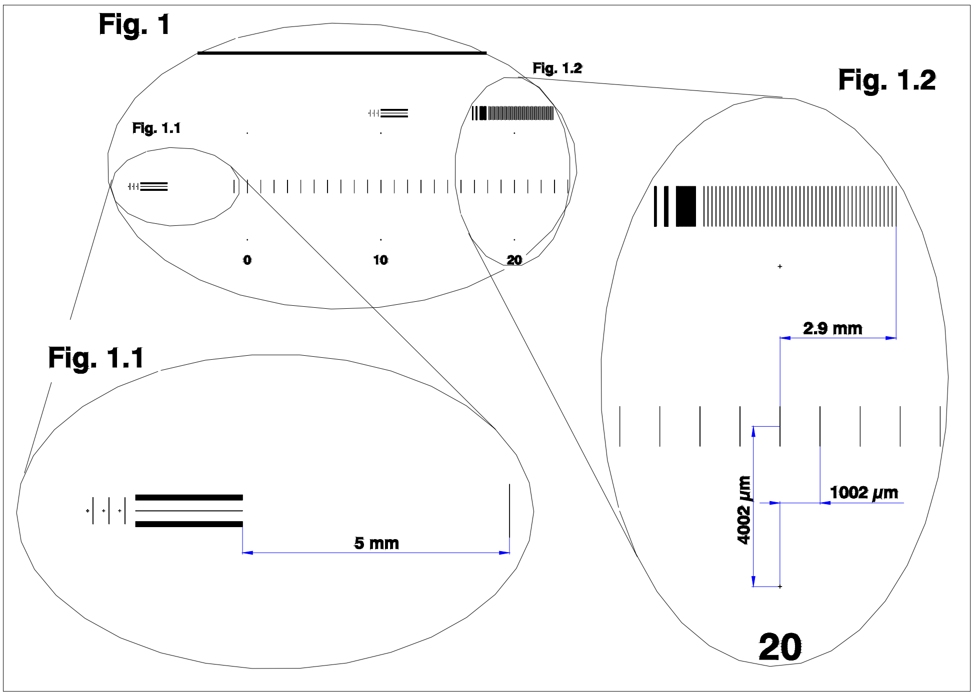
Measurands:

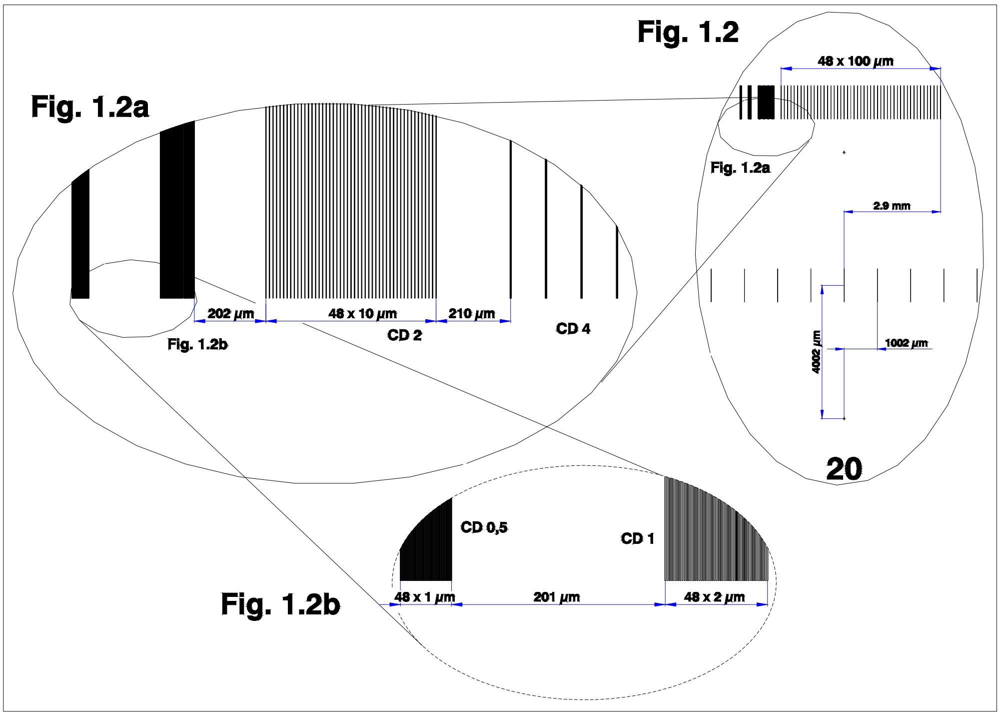


Details:



Details: continued





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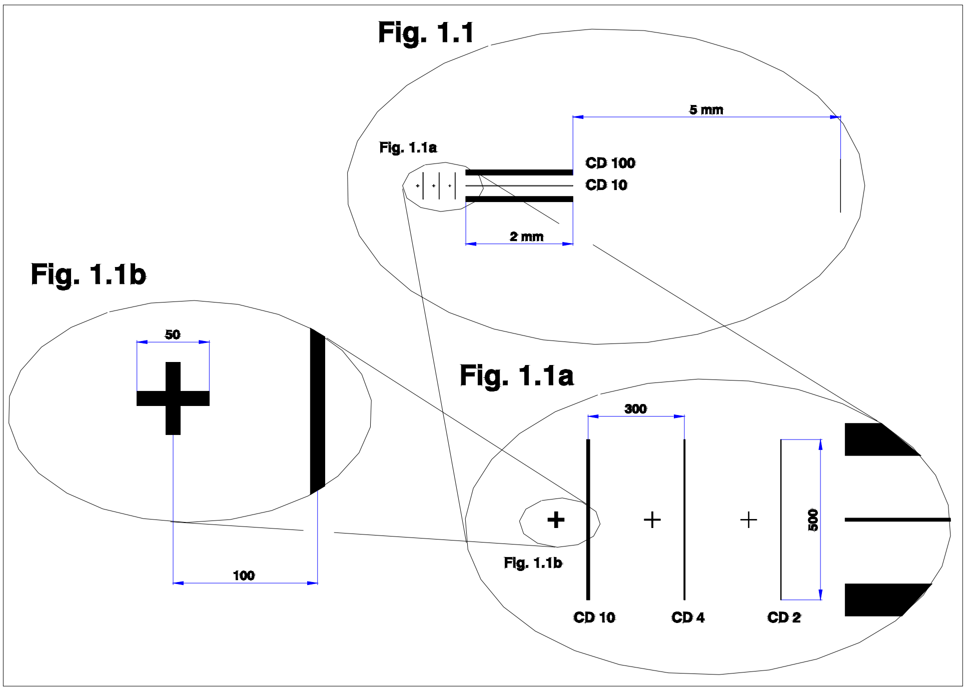
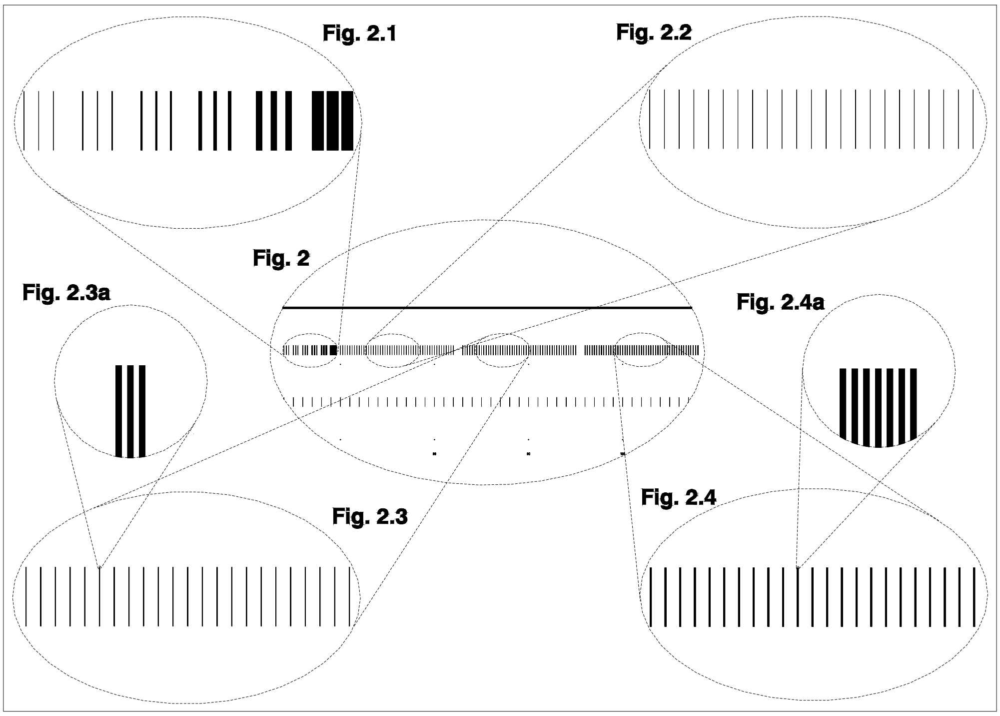
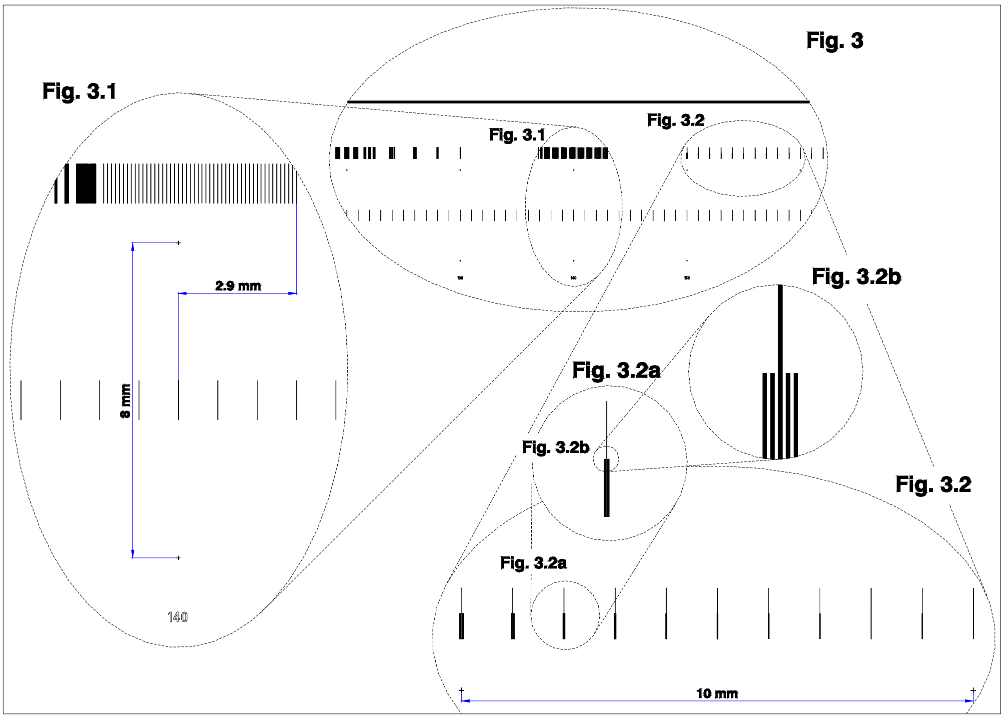
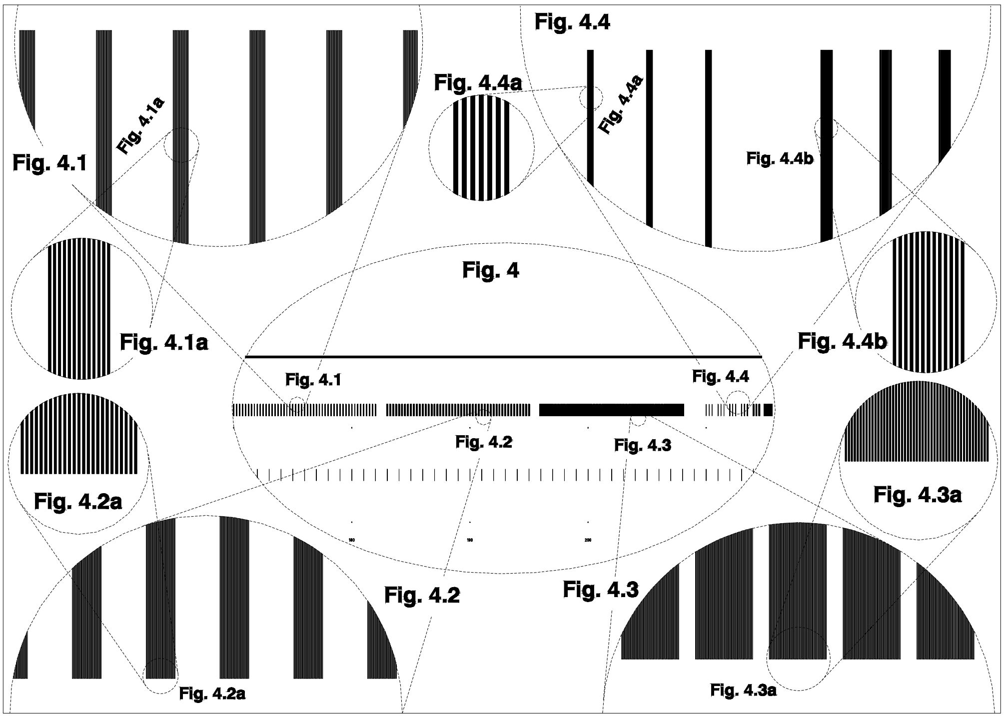




Details: continued





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WGDM-7 Preliminary comparison on nanometrology
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LINE SCALE STANDARDS

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ANNEX C

Description of the measurement methods
and instruments of the participants

Braunschweig, August 29, 2003

PTB, LMS: Measurement report

A) Description of the measurement methods and instruments

Measuring system:

The measurements were performed on a modified 2D photomask measuring system LMS 2020 from Leica which offers a measurement range of 235 mm x 205 mm. The mask comparator consists of an x-y-stage made from Invar which carries the measurement objects and which is supported and guided by air bearings and driven by friction rods. Its position is controlled by means of a two axis differential plane mirror interferometer, see Fig. 1. Additionally a tracking refractometer monitors the changes of refractive index beneath the LMS gantry within a 200 mm Zerodur tube. The tracking refractometer is initialized by measurements of air pressure, temperature, humidity and CO_2-content with external sensors and subsequent calculation of refractive index by the Edlen formula.

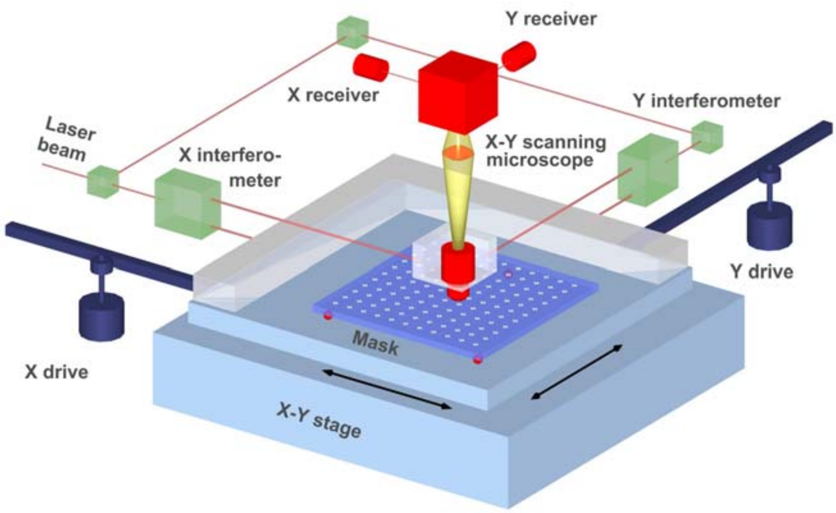


Fig. 1: Basic design of the LMS 2020 photomask measuring system

The edge detection is performed by a special confocal scanning slit type of microscope, which simultaneously measures the intensity of reflected light in two orthogonal directions, which is projected through the microscope objective lens on the sample surface, see Fig. 2 and 3.

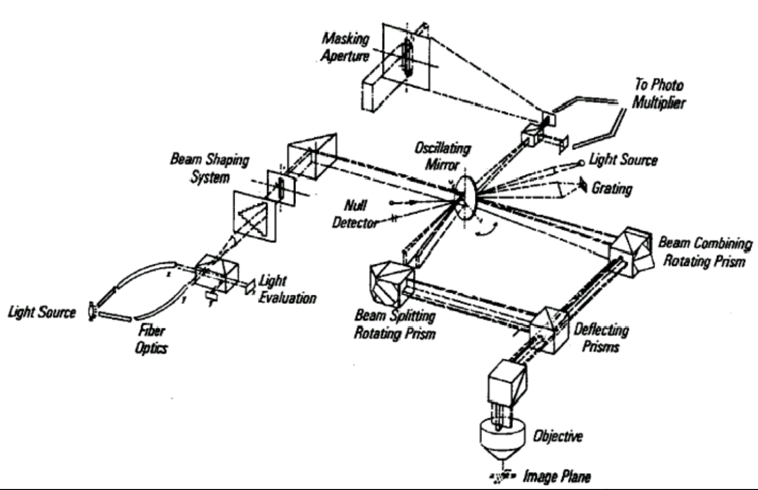


Fig. 2: Principle of LMS x-y-scanning microscope

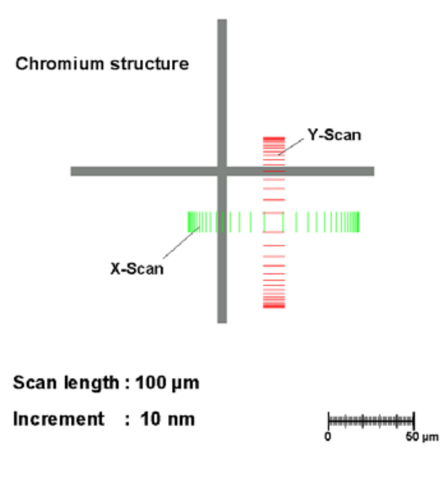


Fig. 3: Simultaneous x-y-scanning

The width of the scanning slit can be adjusted between 1 µm and 12.5 µm, its scanning length on the sample surface is 100 µm and the frequency of the scanning mirror is about 10 Hz. Before the edge measurements process starts, the microscope objective is positioned in optimum focus by means of an independent autofocus measurement system, which operates through the objective lens with light of 830 nm. For illumination of the measurement structures green light with a maximum intensity at about 550 nm is used.

The measurements are performed in static mode. Once the stage is moved, it is held in its target position with activated air bearings, the autofocus procedure is run and the measurement with the scanning slit microscope starts. The time for positioning to a target structure and measuring it takes about 7 s.

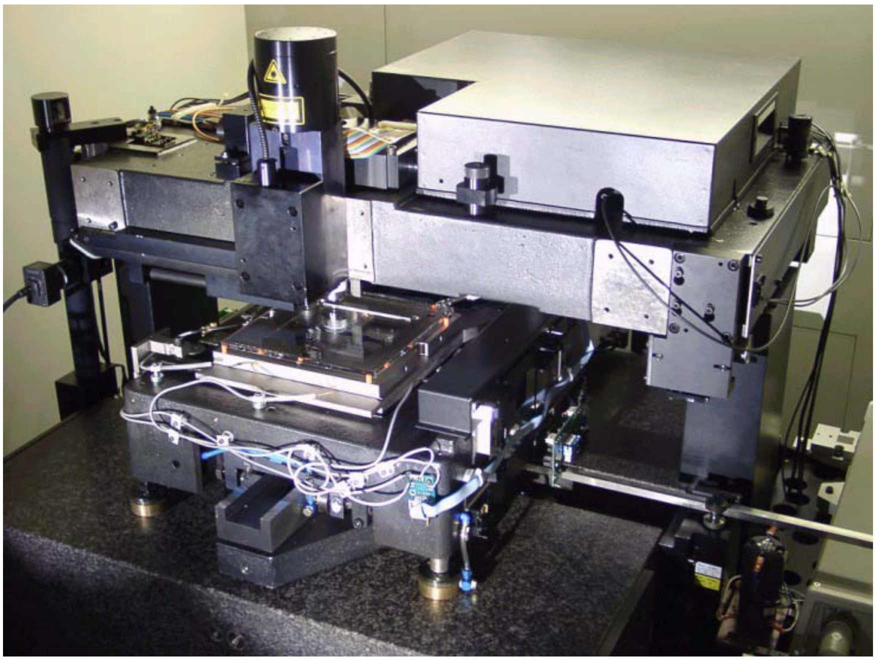


Fig. 4: View of the LMS 2020 photomask measuring system

Line evaluation:

The reflected light intensity of the slit, which is scanned over 100 µm on the surface is digitized with a increment of 10 nm. In parallel to the scanning process, the interferometer readings are taken (about 10.000 intensity and 1000 interferometer readings during every line measurement). The line intensity profiles are analysed by linear regression fits at both edges of the line within an intensity range between 20% and 80%. Finally, the positions of left and right edge are calculated on the basis of the 50% threshold value of the regression lines and the centre line position is the arithmetic mean of both edge positions. Because the largest width of the scanning slit is 12.5 µm only, 9 measurements, each shifted by 12.5 µm along the direction of the line are carried out to get information over the whole 100 µm line section length. The results of the 9 individual measurements were finally processed to get the mean edge positions (weighted mean) and to get information about edge quality (standard deviation over the 9 individual sections).

Scale mounting:

In most cases the line scales were measured along **both** axes of the 2D photomask measuring system. Because the 280 mm main graduation was larger than the positioning range of the stage, the standards had to be measured in two different orientations (0°/180°, 90°/270°) with an overlapping region of 180 mm. Calibrations of the line scales were performed with at least 2 independent initializations of the tracking refractometer.

The scales were supported at the Airy points by a roller and a pivoting edge. The adjustment of the scale to the translational axes could be assured to better than 2 µm/280 mm in vertical direction and to better than 10´´ in horizontal direction.

Corrections:

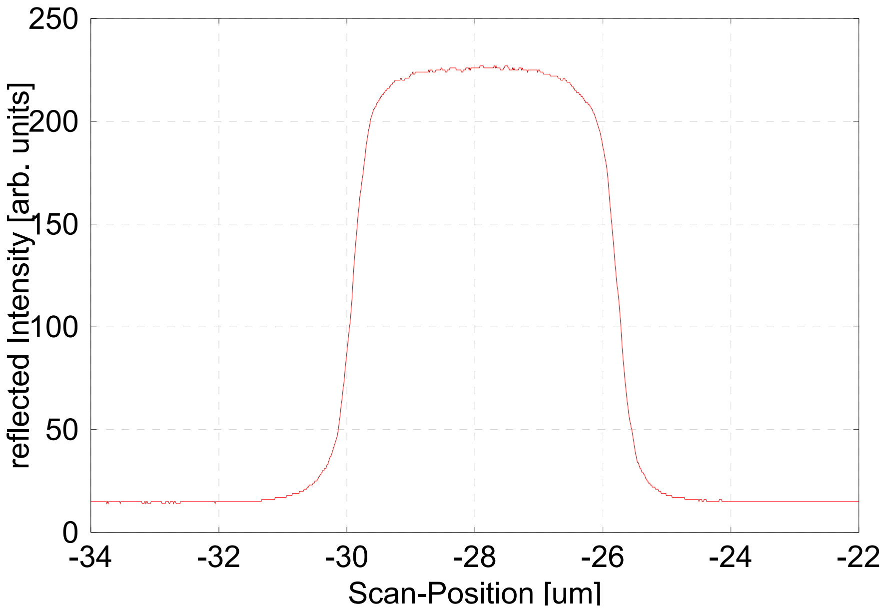
For the final results all known corrections with the coefficients given in the Nano3 technical protocol were applied. In particular, the thermal expansion was corrected using the thermal expansion coefficients of $5.5\cdot10^{-7}$/K for quartz and $3.0\cdot10^{-8}$/K for Zerodur. The temperature deviations from 20°C during the calibrations all were within ±0.05 K. Because the tracking refractometer is made of Zerodur, no compressibility corrections had to be applied to the measurement results on the Zerodur line scale. For the quartz scale, the difference between the length compressibility factors of quartz ($-8.9\cdot10^{-7}$/bar) and Zerodur ($-5.80\cdot10^{-7}$/bar) were chosen for length corrections to the standard pressure of 1013 mbar. However, these correction were smaller than 3 nm, because atmospheric pressure variations during the measurements were within ± 15 mbar. The carbon dioxide content of the air in the measurement room was measured separately. All calibrations were performed under clean room conditions (< 1000).

Initializations:

Initialization of the tracking refractometer was made on the basis of the readings of the instrumentation used to measure the relevant air parameters t, p, RH and CO_2-content. The initialization is influenced by the resolution of the laser tracking interferometer (5 nm/200 mm=$2.5\cdot10^{-8}$). Moreover, temperature gradients beneath the LMS gantry of up to 50 mK between refractometer and interferometer beam paths were measured and had to be taken into account (50 mK corresponds to $\delta n \approx 5\cdot10^{-8}$).

Typical line profile data

Below a profile of the line "140" of the quartz line scale is shown as measured by the LMS microscope with an effective scanning slit width of 12,5 µm (Magnification 100x):



B) Tabular description of the measurement methods and instruments: PTB, LMS

Line detection

Parameters	Parameters used for the measurement
Microscope type:	*Confocal scanning slit microscope, 100x autofocus objective*
Light source	*Mercury high pressure lamp with green interference filter*
Wavelength(s)	*550 nm*
Scanning length	*100 µm length of scanned slit projected onto surface (slit length: 2 µm)*
Slit width	*Adjustable between 1 µm and 12.5 µm; 12.5 was used normally*
Polarization	*x and y- scanning slits detect orthogonal lines with same polarization*
Coherence	
Aperture/magnification	*0.90/100x (2 mm working distance)*
Detection mode	*Record reflected light intensity profile over 100 µm scan length of slit*
Detection principle	*Measure intensity in x and y with lateral increment of 10 nm*
Detection velocity	*V=0 (static detection)*
Sampling frequency (image/interferometer)	*Scanning slit movement at 10 Hz; interferometer readings taken during sampling of reflected light intensity; 12 repeat scans evaluated for one result*
Edge detection criterion	*Line regression fit on both sides (50% threshold; fit range between 20%-80%)*
Edge detection short term repeatability (1s)	*2 nm (includes interferometer readings, nonlinearity)*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands (1σ)
Interferometer light source / wavelength	*Stabilised red He-Ne Laser (HP)*	*2E-9*
Resolution of displac. Interferometer	*single reading: 5 nm* *measurements averaged for one pos. reading*	
Interferometer medium	*Air*	
Refractive index:	*Corrected with Edlen*	
=> refractometer:	-	-
=> Edlen´s formula:	*G. Bönsch et al., Metrologia, 35, 1998*	*1E-8*
Air temperature	*Measured and corrected*	*0.02 K*
Air pressure	*Measured and corrected*	*0.05 mbar*
Air humidity	*Measured and corrected*	*1.5 % rel. H*
CO_2-content	*Measured and corrected*	*70 ppm*
Guide error	*1 arcsec*	*0,2 arcsec*
Abbe offset	*0 mm*	*<0.5 mm in z ; <1 mm in x,y*
Alignment error:		
Interferometer	*< 30´´*	*15´´*
Scale	*±2 µm in z, <10´´ in x and y*	

2 OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	Measured and compensated	0.025 K *(temp. inhomogeneity)*
Number of repeat measure ments in one scale position	*15 times,* *measurements in 9 separate line sections (each 12.5 µm in width)*	
Number of scale orientations	*Scale in 2 overlapping reversed orientations; scales oriented along x and y-axis*	
kind of support	*Roller and pivoting edge*	
clean room class	*< class 1000*	

Measurand 1B: Deviations from nominal length, every 5 mm line, Zerodur: PTB-LMS

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Stage:					
Error due to Abbe offset in z (a_p<0.5 mm) and pitch, δl_{Ap}	R	2,8 µrad	100	a_p·/rad	1.4
Error due to Abbe offset in x, y (a_y<1 mm) and yaw, δl_{Ay}	R	2,8 µrad	100	a_y·/rad	2.8
Interferometer:					
Laser vacuum wavelength, stab. $\delta\lambda_o$	N	6 fm	10	L/λ_0	0.006 L
Air temperature, t_{air}	N	20 mK	7	9.6x10^{-7} L /K	0.018 L
Air pressure, p_{air}	N	5 Pa	4	2.7x10^{-9} L /Pa	0.014 L
Relative Humidity, RH_{air}	N	1.5%RF	4	8,5x10^{-9} L /RH%	0.013 L
Air CO_2 concentration, c_{CO2}	N	70 ppm	4	1.5x10^{-10} L /ppm	0.011 L
Edlen equation uncertainty, δn_{air}	R	1x10^{-8}	100	L	0.010 L
Resolution of tracking refract., δn_{res}	R	2.9 nm	100	(1/200mm) L	0.015 L
Temperature gradient between refractometer / measurement beam	R	18 mK	100	9.6x10^{-7} L /K	0.017 L
Interf. cosine error δl_{Ii} (µrad)	R	82 µrad	100	4.1x10^{-5} L/rad	0.0034 L
Diffraction effect of the laser beam, δl_{dif} (≈L*(λ_0/(π*D)²; D=6 mm)	R	1.2x10^{-9}	100	L	0.0012 L
Scale:					
Scale temperature difference from 20 °C, Δt_s	N	25 mK	7	3x10^{-8}L/K	0.00075 L
Linear coefficient of thermal expansion, α_Z	N	2x10^{-8} 1/K	10	L ·0.05 K	0.001 L
Bending infl.: Support variation ±1 mm => dl<±3 nm @ 280 mm	R	1.8 nm	100	3.6x10^{-9} L /nm	0.006 L
Errors of scale alignment & cosine error, δl_{Si}. δl_{Ii}	R	4.2 µrad	100	2x10^{-6} L /rad	0.000008 L
Influence of line edge quality δ_{Ealg}	N	3 nm	9	1/(2$^{1/2}$)	2.2
Measurement:					
Scale difference between indep. tracking initializations (experience)	N	3x10^{-8}	2	L	0.030 L
Scale difference between x and y meas. results (experience)	N	2.5x10^{-8}	2	L	0.025 L
Scale difference between 0° and 180° orientation (experience)	N	2x10^{-8}	2	L	0.020 L
Repeatability of edge pos. results. (short term repeatability.), s	N	2 nm	14	1	2.0

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(L)$= Q[4.4; 0.062·L] nm, L in mm, Q[x; y]=$(x^2+y^2)^{½}$

Effective degree of freedom: $\nu_{eff}(L)$= 19 @ L = 280 mm;

Expanded uncertainty: $U_{95}(L)$= Q[9; 0.13 L] nm, L in mm (k=2.1)

NIST: Measurement report

A) Description of the measurement instruments and methods

Both 280 mm scales were measured with the NIST Line Scale Interferometer (LSI). The LSI consists of a scanning electro-optical line detector, a high precision one-axis motion system, and a high accuracy heterodyne interferometer for determining the displacement of the test artifact beneath the line detector. The wavelength of a stabilized helium-neon laser corrected for temperature, humidity, atmospheric pressure and CO_2, is used as the length standard. The instrument is housed in an environmental chamber in which all environmental properties are carefully monitored. The complete description of the design and operation of the NIST LSI is given in the Journal of Research of the National Institute of Standards and Technology Volume 104, Number 3, May-June 1999, *" The NIST Length Scale Interferometer."*

Reflected light was used to obtain line images. Both scales were measured in the horizontal position with scale face up and supported at the Airy points as marked on the side of each scale. At one support point a two inch wide stainless steel wedge, covered with a thin textured latex material, was used and was fixed to the Invar scale support to which the interferometer cube-corner reflector also was attached. At the other point the scale was supported on a stainless steel roller supported at its center point. The wedge support was used to avoid slippage of the scale, due to inertia, during measurement, and the roller support prevented a twisting force on the scale as well as allowing free expansion and contraction of the scale.

On the main scale there were three independent measurements. From zero to 20 mm with 1 mm steps, from zero to 280 mm with 10 mm steps and from zero to 280 mm with no intermediate steps. On the auxiliary scale from zero to 4.6 mm the scale was measured in five sections independently and the sections were added together. The zero to 0.46 mm scale also was measured the same way. This break up was necessary to shorten the measurement time to minimize the adverse effect of fluctuating atmospheric pressure.

Measurements were made from line center to line center using a graduation line segment of 0.08 mm long, extending 40 µm above and 40 µm below the alignment lines on the scale surface. Data was recorded by averaging 400 interferometer readings when the scale was stopped and servo-locked at each measured graduation line.

The environmental chamber and scale temperatures were held within ±0.005 °C of 20 °C during the measurements. The air temperature was measured close to the path of the interferometer laser beam and scale temperature was measured at three locations along the scale and the mean temperature was used for scale length corrections. The lengths are reported at a temperature of 20 °C (68 °F). A coefficient of linear thermal expansion of 3×10^{-8} / °C for the Zerodur scale and 0.55×10^{-6} / °C for the quartz scale were used in normalizing the lengths to 20 °C. During measurements the average atmospheric pressure was 99825 Pa and the average relative humidity was 50%.

B) Tabular description of the measurement methods and instruments: NIST

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Scanning photoelectric microscope (See Ref. #1 p. 230)
Light source	White light
Wavelength(s)	≈ .7 to .4 μ*m*
Slit length	0.08 mm
Slit width	0.1 mm
Polarization	none
Coherence	NA
Aperture/magnification	100
Detection mode	Line image detected by photomultiplier
Detection principle	The left and right line edges are simultanously detected and the line center derived by the servoing line detector circuit. (See Ref. #1 p. 230-231)
Detection velocity	0
Sampling frequency (image / interferometer)	400 readings / sample
Edge detection criterion	Edges are detected at the 50 % intensity level. (See Ref. #1 p. 232)
Edge detection short term repeatibility (1s)	1 nm or less

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement expanded uncertainty for measurands
Interferometer light source / wavelength	632.991350 nm	0.000000451nm
Resolution of displacement Interferometer	1 nm	
Interferometer medium	Air	
Refractive index:		
=> refractometer:	NA	
=> Edlen's formula:	Revised 1994	2×10^{-8}

Parameters	Parameters normally used for the measurement equipment	Achievable measurement expanded uncertainty for measurands
Air temperature	20.000 °C ±0.005 °C	0.001°C
Air pressure	99000 to 101000 Pa	4 Pa
Air humidity	20 to 50 %R.H.	1.2 %
CO_2-content	380 ppm	25 ppm
Guide error	1.5 arc sec / m	0.1 arc sec
Abbe offset	0	0.2 mm
Alignment error:	0.06 arc sec	
Interferometer	H.P. 10565 interferometer	1 nm
Scale	1 m length	100 nm / m

Other measurement conditions

Parameters	Parameters normally used for the measurement equipment	Achievable measure-ment expanded uncertainty for measurands
Scale temperature	20.000 °C ± 0.005 °C	0.001 °C
Number of repeat measurements in one scale position	4 measurements	
Number of scale orientations	2 orientations	
Kind of support	The scale is supported at the Airy points, on a wedge at one point and on a (one point supported) roller at the other point.	
Clean room class	Class 10000	

Reference:

1. The NIST Length Scale Interferometer, John S. Beers and William B. Penzes, Journal of Research of the National Institute of Standards and Technology, Volume 104, Number 3, May-June 1999.

C) Description of the measurement uncertainty: NIST

Results of the measurements are given on the following pages of this report. The length

$$U_{95} = ku_c$$

values are the mean of eight measurements and the expanded uncertainty is

$$u_c = \sqrt{(u_i^2 + u_j^2)}$$

where u_i is the type-A standard uncertainty and u_j is the type-B standard uncertainty. A coverage factor $k=2.36$ was used which gives for the reported value a level of confidence of 95 percent.

The u_i uncertainty was derived from the measurement result and includes several input quantities which cannot be separated. These uncertainties include those contributed by laser interferometer polarization mixing, scale surface and graduation lines quality, measurement repeatability, line edge detection and line center derivation, measured length difference between normal and reverse scale orientation, measured length deviation due to sudden pressure changes during interferometer readings, and vibrational noise in the measurement system, just to mention a few.

The u_i standard uncertainty is one standard deviation of the mean value and is computed from

$$u_i = \frac{\sqrt{\Sigma \frac{d^2}{N-1}}}{\sqrt{N}}$$

the formula
where d is the deviation of a single measurement from the mean, N-1 is the number of degrees of freedom (7) and N is the number measurements (8)

On each scale the reported u_i values in each interval group is the RMS value of all u_i values within that group. (0 to 280 mm, 0 to 20 mm, 0 to 4.6 mm and 0 to 0.46 mm.)

The u_j standard uncertainty was derived from the sum of several systematic uncertainties

$$u_j = \sqrt{\left(u_{\lambda_0}{}^2 + u_{n_{tpf}}{}^2 + u_{t_a}{}^2 + u_{ts}{}^2 + u_p^2 + u_{rh}^2 + u_{co_2}{}^2 + u_{align}^2 + u_\alpha^2\right)}$$

present in the measurement system:

where the evaluated systematic uncertainties are

λ_0	the vacuum wavelength of the laser (20 nm/m)
n_{tpf}	the refractive index equation (20 nm/m)
t_a	the air temperature in the interferometer path (less than 3 nm/m)
t_s	the scale temperature (1 nm/m for quartz or Zerodur)
p	the atmospheric pressure in the laboratory (20 nm/m)

rh the Relative Humidity in the measuring chamber (10 nm/m)
co_2 the carbon dioxide in the laboratory (10 nm/m)
align. the interferometer and scale alignments (20 nm/m)
α the expansion coefficient of the scale (less than one nm/m)

u_j = 50 nm / m was used in the measurements

The u_j length dependent systematic uncertainties were included only in the main scale measurement uncertainties. In the auxiliary scale measurements the u_j uncertainties were not included because their contribution was negligible.

UNCERTAINTY OF MEASUREMENT: EXAMPLE FROM NIST

Measurand 1B: Deviation from nominal length for every 10 mm graduation line, Zerodur

Combined standard uncertainty: $u_c\ (dl) = [(5.2\ \text{nm})^2 + (5\text{x}10^{-8} \text{ x L})^2]^{1/2}$

Effective degree of freedom: $\nu_{eff}\ (dl) = 7$

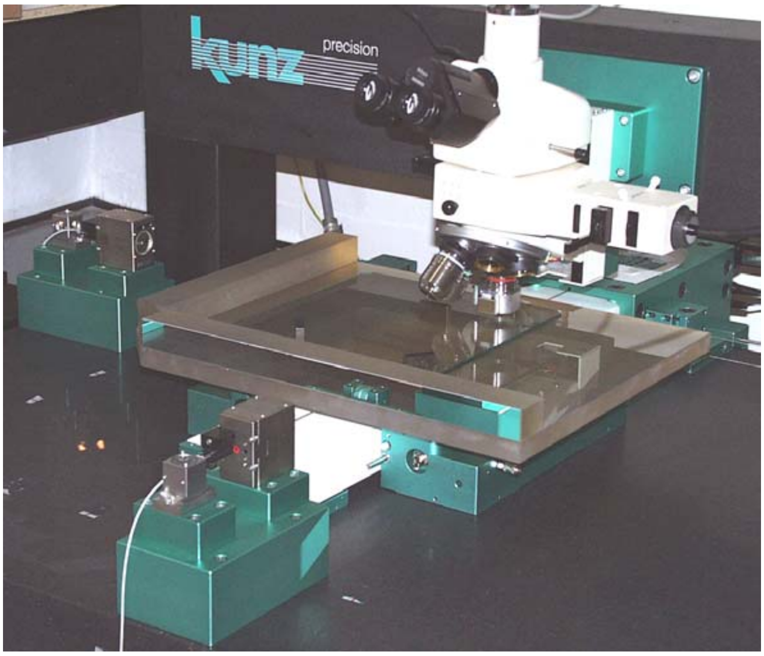
Expanded uncertainty: $U_{95}\ (dl) = [(5.2\ \text{nm})^2 + (5\text{x}10^{-8} \text{ x L})^2]^{1/2} \text{ x } [2.36]$

METAS: Measurement report

A) Description of the measurement methods and instruments

Measuring system:

The measurements were performed on a 2D photomask measuring system with a measurement range of 400 mm x 300 mm. The system has an xy-stage with unique vacuum air-bearings featuring very small errors of motion. Two speed controlled servo motors move the table through fine strings. Once positioned, the stage is clamped to the granite base table by vacuum. A differential two axis plane mirror interferometer (HP) measures the position of the stage. The moving mirrors are attached to a Zerodur base plate and the reference mirrors are fixed to the microscope objectives. Air pressure, temperature, humidity and CO_2 content are on line accessed to determine the refraction index of the air by the Edlen formula. A microscope with a CCD camera and an episcopic illumination is used to localise the line positions. The microscope has a motorised turret and focus. For automatic focussing the image contrast is maximised. For the illumination green light of approx. 550 nm was used.



Line evaluation:

Each horizontal line profile within the region of interest (ROI) in the image is analysed. The centre of the left and the right edge is used and the edge locations are determined with a moment based edge operator. A line is fitted through all these centres using only points within 2σ. The intersection of this fitted line with the reference line, given by the alignment marks on the scale, is used as the scale line position.

Scale mounting:

The line scales were aligned parallel to the x-axis of the 2D photomask measuring system. They were supported at the Airy points by 4 spheres, two on a pivot. The Zerodur base plate of the xy-stage connects the scale supports to the mirror. The scales were aligned with piezo-electric actuators. Vertically to better than 1 µm/280 mm and horizontally to better than 4 µm/280 mm. Additionally, as a 2D measuring system is used, the x-axis of the object coordinate system is placed trough the alignment marks.

Measurement strategy:

The 2D photomask measuring system can operate fully automatically, therefore a complete set of measurements was made during night-time lasting for about 9 hours. Such a set of measurements consisted of the following:

Scale (mm)	**Lines**	**Repetitions**
0 .. 280	2	50
0, 40 .. 280	8	10
0, 5 .. 280	57	4
0 .. 20	2	50
0, 1 .. 20	21	4
0.1 .. 4.7	2	50
0.1, 0.2 .. 4.7	47	4
0.01 .. 0.47	2	50
0.01, 0.02 .. 0.47	47	4

Both line scales were measured in two orientations 0° and 180° and with two objectives 20x and 50x. For the final result all these measurements were averaged There was no systematic difference.

Corrections:

For the final results all know corrections were applied. In particular, the thermal expansion was corrected using the given thermal expansion coefficients of 5.5E-07/K for quartz and 3.0E-08/K for Zerodur. The temperature deviations from 20°C were within ±0.1 K. Furthermore, as the measuring system is located 570 m above sea level, the average barometric pressure during the measurements was only around 950 mbar and the scales were therefore too long. The results were reduced to the standard pressure of 1013 mbar with the given compressibility factors of -8.90E-07/bar for quartz and -5.80E-07/bar for Zerodur. The corrections amounted to 15.2 nm (quartz) and 9.6 nm (Zerodur) for 280 mm.

Uncertainty contributions:

For the total uncertainty 30 contributions were considered. The largest contributions at 280 mm were for both scales the air temperature, the air pressure, the repeatability and the line evaluation method. For the quartz scale also the material temperature was critical. Glass has a low thermal conductivity and a small thermal capacity therefore it is difficult to measure its temperature. In our current laboratory the temperature inhomogeneity limits the accuracy of the air temperature measurement. The accuracy of the thermistors itself is not the problem.

Within the next 3 month the measurement system is moved into a specially conceived clean room cabin in a new building.

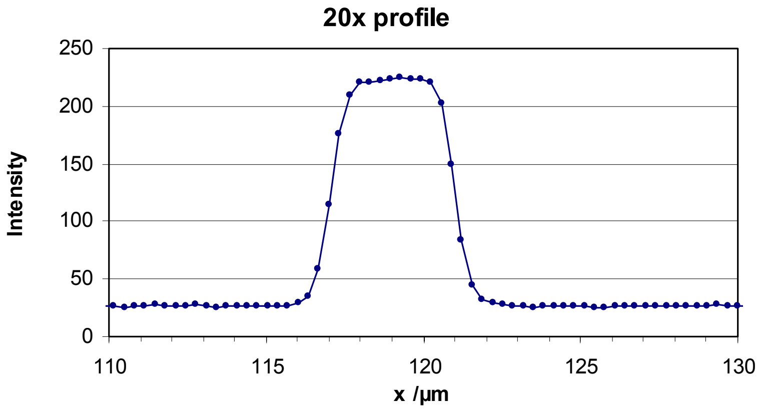
Typical image and line profile data

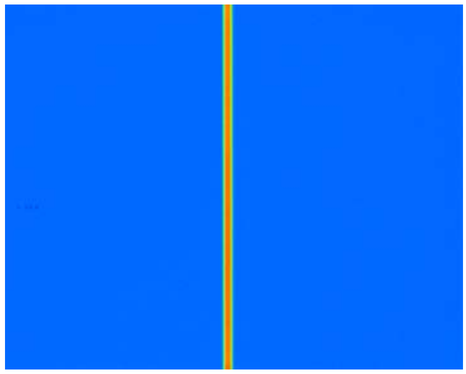
Below images and profiles of the line "0" of the quartz line scale are shown as taken by the 20x and the 50x objective of the microscope.

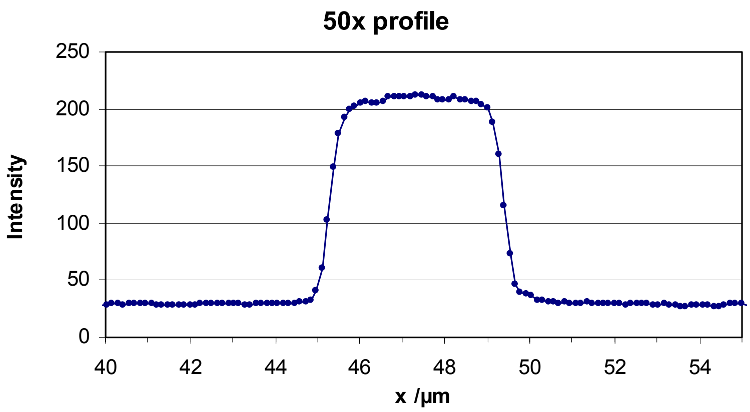
Table: Image size and evaluation range.

2.1 MAGNIFICATION		**20x** µm	**50x** µm
Image size:	**x**	244	98
	y	182	73
Evaluation range:	**x**	11	11
	y	100	72

Magnification 20x:







B) Tabular description of the measurement methods and instruments: METAS

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Video microscope with episcopic illumination, 20x and 50x objectives
Light source	*cold light source with green interference filter*
Wavelength(s)	*550 nm*
Slit length	*CCD detection -> adjustable (20x: 100µm; 50x: 71 µm)*
Slit width	*CCD detection -> adjustable about 11µm*
Polarization	*None*
Coherence	-
Aperture/magnification	*0.46/20x or 0.90/50x*
Detection mode	*Digital image evaluation*
Detection principle	*Black and white CCD with pixel sync.*
Detection velocity	*V=0 (static detection)*
Sampling frequency (image/interferometer)	*4 frames at 10frames /second –interferometer readings before and after each frame (i.e. 8 interefometer readings per line)*
Edge detection criterion	*Moment based edge detection on both sides (left and right)*
Edge detection short term repeatability (1s)	*4nm for 20x and 50x*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands (1σ)
Interferometer light source / wavelength	*Stabilised red He-Ne Laser (HP)*	*8E-9*
Resolution of displac. Interferometer	*5 nm single mesurement* *100 measurements averaged for one reading -> due to noise higher resolution*	
Interferometer medium	*Air*	
Refractive index:	*Corrected with Edlen*	
=> refractometer:	*No*	-
=> Edlen´s formula:	*G. Bönsch et al., Metrologia, 35, 1998*	*1E-8*
Air temperature	*Measured and corrected*	*0.05 K (temp. inhomogeneity)*
Air pressure	*Measured and corrected*	*0.05 mbar*
Air humidity	*Measured and corrected*	*0.75 % rel. H*
CO_2-content	*Measured and corrected*	*60 ppm*
Guide error	*0 arcsec*	*5 arcsec*
Abbe offset	*0 mm*	*<0.5 mm in z 0 / <1 mm in x,y*
Alignment error:	*< 130µrad*	
Interferometer	*HP differential plane mirror interferometer*	*2nm NL*
Scale	*none*	

3 OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	Measured and compensated	0.04 K *(temp. inhomogeneity)*
Number of repeat measure ments in one scale position	*4 to 50 times*	
Number of scale orientations	*Two*	
kind of support	*4 spheres, two on a pivot*	
clean room class	*Roughly class 100'000*	

Measurand 1B: Deviations from nominal length for every 5 mm line, Zerodur: METAS

3.1 UNCERTAINTY OF MEASUREMENT

name and symbol x_i (unit)	distrib.	$u(x_i)$	ν_i	for 280 mm $c_i = dl/dx_i$	$u_i(dl)$ /nm	const $u_i(dl)$ /nm	rel. to L $u_i(dl)$ /L
Translation stage:							
Yaw of x-axis δl_{yaw} (µrad)	R	0.7	100	5.77E-07	0.23	0.23	
Pitch of x-axis δl_{pitch} (µrad)	R	0.7	100	2.89E-07	0.12	0.12	
Parameter: Abbe offset x δl_{Ax} (mm)	R	0.5					
Parameter: Abbe offset z δl_{Az} (mm)	R	1					
Interferometer:							
Vacuum wavelength λ_0 (nm)	N	5E-06	10	4.42E-01	2.21		7.9E-09
Air temperature t_{air} (°C)	R	0.05	8	2.53E-04	7.29		-2.6E-08
Air pressure p_{air} (mbar)	N	0.05	4	7.51E-05	3.76		1.3E-08
Air humidity RH_{air} (%rel.)	N	0.75	4	2.38E-06	1.78		-6.4E-09
Air CO2 concentration c_{CO2} (ppm)	R	60	4	3.87E-08	1.34		4.8E-09
Edlen equation n_{air} (rel.)	N	1E-08	100	2.80E+02	2.80		1.0E-08
Interf. Deadpath δl_{DP} (mm)	N	10	10	1.55E-07	1.55	1.55	
Parameter: Change of n (1)	R	3E-07					
Interf. nonlinearity δl_{NL} (nm)	R	2	10	1.00E-06	1.15	1.15	
Interf. cosine error δl_{li} (µrad)	R	130	10	1.82E-08	1.37		4.9E-09
Imaging:							
Microscope magnification Mag (%)	R	0.2	10	5.77E+00	0.67	0.67	
CCD orientation $\delta\,\alpha_{CCD}$ (°)	R	0.01	10	1.75E+01	0.10	0.10	
Parameter: x-positioning d_{pos} (µm)	R	1					
Image distortion δ_{Enon} (%)	R	0.05	10	2.00E+01	0.58	0.58	
Parameter: half linewidth HLW (µm)	N	2					
Microscope focus stage:							
Focal lenght variation δ_{Efoc} (µm)	R	0.2	10	1.00E-06	0.12	0.12	
Microscope alignement xz δ_{Ealign} (°)	R	0.12	10	3.49E-06	0.24	0.24	
Ref. mirror alignement xz $\delta_{RMalign}$ (°)	R	0.03	10	1.75E-05	0.30	0.30	
Pitch of z-axis zx δ_{Epitch} (µrad/µm)	R	0.015	10	1.91E-05	0.17	0.17	
Roll of z-axis δE_{roll} (µrad/µm)	R	0.01	10	1.00E-06	0.01	0.01	
Parameter: focus-range dF (µm)	R	1					
Param.: Int. ref. beam offset (mm)	R	19.05					
Scale properties:							
Scale alignement horiz. δl_{Sh} (µrad)	R	17.86	10	2.50E-09	0.03		9.2E-11
Scale alignement vert. δl_{Sv} (µrad)	R	3.571	10	5.00E-10	0.00		3.7E-12
Temperature deviation Δt_s (K)	N	0.04	10	8.40E-06	0.34		1.2E-09
Thermal exp. coef. α_z (1/K)	R	4E-08	10	2.80E+01	0.65		2.3E-09
Pressure variation s_{pair} (mbar)	R	10	10	1.62E-07	0.94		-3.3E-09
Compressibility κ_Z (1/bar)	R	2E-08	10	1.68E+01	0.19		6.9E-10
Scale support δ_{supp} (nm/280mm)	N	2	10	1.00E-06	2.00		7.1E-09
Measurement line def. δ_{lpos} (µm)	R	2	10	3.02E-07	0.35	0.35	
Parameter: Line parallelity (°)	R	0.03					
Line quality and evaluation δ_{Ealg} (nm)	N	8	8	1.00E-06	8.00	8.00	
Illumination inhomogenity δ_{Illum} (nm)	R	1	4	1.00E-06	0.58	0.58	
Measurement:							
Repeatability of line det. s_E (nm)	N	5	16	1.00E-06	5.00	5.00	

name and symbol x_i (unit)	distrib.	$u(x_i)$	ν_i	for 280 mm $c_i = dl/dx_i$	$u_i(dl)$ /nm	const $u_i(dl)$ /nm	rel. to L $u_i(dl)$ /L
	Total	U_c (1S)			13.7	9.7	3.4E-08
	Total	U_{95}			27.7	19.7	7.0E-08
	General expression:			**U_{95} = Q (20 nm ; 7.0E-08*x)**			

Formula or expression of uncertainty shall be given in the same way as for MRA C:

In general for any length L: u_c = Q (10 nm ; 3.4E-08*L)

U_{95} = Q (20 nm ; 7.0E-08*L)

with $Q(a,b) = (a^2+b^2)^{1/2}$

For 280 mm:

Combined standard uncertainty: $u_c(dl)$ = 13.7 nm

Effective degree of freedom: $\nu_{eff}(dl)$ = 36

Expanded uncertainty: $U_{95}(dl)$ = 27.7 nm

CMS /ITRI: 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..

The measuring method of the standard scale calibration system is carried out by a graduation center positioning setup. It consists of a microscope, a CCD, an image processing card, a laser interferometer, a servo control card, a positioning stage, a DC servomotor and other equipments. When the graduation is in view of the microscope and the CCD, 640×480 pixels with a 128 gray level image is a token from the CCD. The computer analyzes this image by scanning 100 horizontal reference line's gray level value. From the intensity of the gray level, the computer calculates the center of the graduation. After analyzing an average of 100 lines, a image processing technique is used to calculate the deviation between the graduation center and the CCD center. The deviation signal is sent back to the PZT to make small movements until the graduation center is overlaped with the CCD center. Meantime, the displacement of the carriage of graduation to be calibrated is detected by the laser interferometer. Then move the carriage to the next calibrated graduation. The calibration system block diagram is shown in Figure 1.

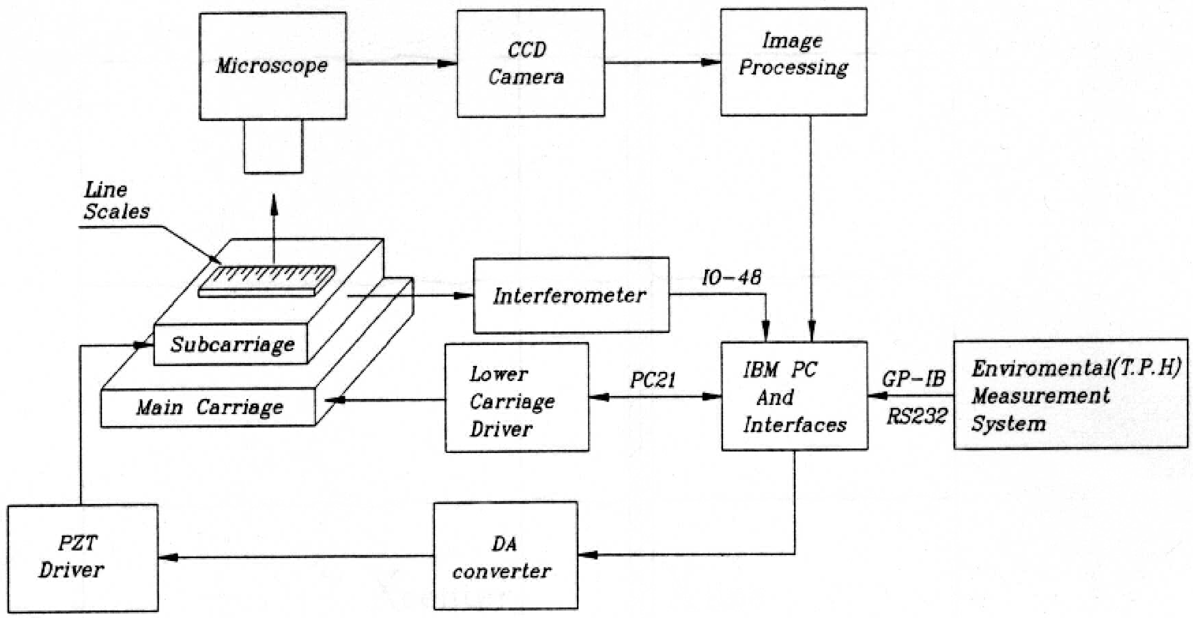


Figure 1. Schematic diagram of the standard scale calibration system

B) Tabular description of the measurement methods and instruments: CMS/ITRI

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Optical micrescope with CCD carema
Light source	Halogen bumb
Wavelength(s)	--
Slit length	--
Slit width	--
Polarization	--
Coherence	--
Aperture/magnification	0.80 / 50X
Detection mode	the power of gray level
Detection principle	Image processing technique
Detection velocity	*Statical*
Sampling frequency (image/interferometer)	*e.g. # of images per line ?; synchroneous reading of signal and interf. ?*
Edge detection criterion	2/3 of the difference of grey level of (max – min) piexels
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	The red light Zeeman stabilized He-Ne laser, the wavelength is 0.632991359 µm.	
Resolution of displac. Interferometer	1/64 of wavelength	
Interferometer medium	air	
Refractive index:		
=> refractometer:	--	
=> Edlen´s formula:	Edlen's formula for the refraction index of air after the revision by G. Bönsch	
Air temperature	The air temperature is measured by SPRT with an electrical bridge (ASL F17A) , compare the resistance of SPRT with standard resistance.	
Air pressure	barometer	
Air humidity	relative humidity recorder	
CO_2-content	CO_2 content sensor	
Guide error		
Abbe offset		
Alignment error:		
Interferometer		
Scale		

4 OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	0.1□ varied from the air	
Number of repeat measurements in one scale position	*>21*	
Number of scale orientations	*1*	
kind of support	*Airy points*	
clean room class	--	

Measurand 1B: Deviations from nominal length for every 5 mm line: CMS/ITRI

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Laser wavelength (λ_0)	N	1.25×10^{-9} m	50	1.58×10^{-3}L	0.00198 L
Laser resolution (δl_{Res})	R	2.86×10^{-9} m	50	1	2.86
Refraction index of air (n_{air})	N	1×10^{-8}	50	1×10^{6}L nm	0.01 L
Air temperature(t_{air})	R	0.013 °C	12.5	9.49×10^{-1}L nm/°C	1.23×10^{-3}L
Air pressure (p_{air})	N	10 Pascal	50	2.68×10^{-3}L nm/Pascal	0.0268 L
Relative humidity(RH_{air})	N	2% R.H.	50	8.67×10^{-3}L nm·%R.H^{-1}	0.0173 L
CO_2 content (C_{CO2})	N	37 ppm	12.5	1.476×10^{-4}L nm/ppm	0.0055 L
Scale thermal expansion coefficient (α_S)	N	4×10^{-8} °C^{-1}	12.5	1×10^{5} L nm·°C	0.004L
Scale temperature (Δt_s)	T	0.041 °C	12.5	0.55L nm·°C^{-1}	0.023
Scale vertical alignment error (δ_{Efoc})	R	0.375 µm	12.5	4.85×10^{-14}L	1.82×10^{-11}L
Scale horizontal alignment error (δl_{Si})	R	0.289 µm	12.5	3.73×10^{-14}L	1.08×10^{-11}L
Straightness error (δl_{Ai})	R	0.289 mm	12.5	3.64×10^{-6}	1.05
Laser alignment (δl_{li})	R	5.6×10^{-5}	12.5	56 L nm	0.00313 L
Carriage temperature variance (Δt_b)	T	0.0051 °C	12.5	10 L nm·°C^{-1}	0.051 L
CCD resolution (δ_{Eres})	R	0.074 µm	50	1	74
Repeatability (S_E)	N	0.0115 µm	31	1	11.5
Errors of Measurement Path (δl_{MP})	N	0.0288 µm	28	1	28.8

(L is the value of length without mm)

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(dl)$ = 83 nm

Effective degree of freedom: $\nu_{\mathrm{eff}}(dl)$ = 73

Expanded uncertainty: $U_{95}(dl)$ = 164 nm

NIM: **Measurement report**

A) Description of the measurement methods and instruments

The line scale standards of Nano3 was measured in Gauge Block and Line Scale Laboratory, Length Division, NIM. The comparator used for comparison measurement is made by NIM, which consists of He-Ne Laser with the wavelength 633 nm, main Interferometer, optical-electronic microscope, moving table, driving system, base, temperature measuring system, electronic part, computer and software. The interferometer is Mechlson type with resolution of 80 nm. The optical-electronic microscope uses dual slit to detect line position. Because the scale is transparent, the transmission light was used. Measurement starts from first line and continues till last line.

It took two weeks to finish total measurement. The kind of support is line contact. Four supports were used, whose positions were on the bessel points marked on the scale. The scale was in series with the main beam path of interferometer with Abbe-error free. Scales were measured in two orientations. In one orientation two repeating measurements were made as one group. Then scale were reinstalled in reverse orientation and the instrument was readjusted such as focus and alignment and so on to eliminate possible system error. 36 groups of measurements were made, which means the Number of measurement of each scale is 76. The end result is the average of total measurement.

Measuring environment condition is as following:

Measuring place:	normal laboratory room	
Room temperature:	20°C±0.5°C	
Scale temperature:	Zerodur:	20°C ±0.2°C
	Quartz:	20°C ±0.3°C
Humidity:	normal	
Air pressure:	1020.5±3.0 Pa	

About measuring uncertainty:

We have got the standard measuring uncertainty of

Zerodur is $u_c = \sqrt{(51.4\,\text{nm})^2 + (4.6\times 10^{-8}\,\mathrm{d}L)^2}$

Quartz is $u_c = \sqrt{(51.4\,\text{nm})^2 + (4.7\times 10^{-8}\,\mathrm{d}L)^2}$

Which shows that the difference of measuring uncertainty of two scales is very small. Therefore we used one expression to represent both of them, which is $u_c = \sqrt{\sum_{i=1}^{18} u_i^2} = \sqrt{(51.4\text{ nm})^2 + (4.65\times 10^{-8}\,\mathrm{d}L)^2}$

From this expression, we know that the standard uncertainty is only increased from 51.4 nm to 53nm when measuring length dL changes from 0 mm to 280 mm. For simpleness, we neglect the items, which are concerned to length dL. And use following expression as standard uncertainty of both scales:

$$u_c = 53\text{ nm}$$

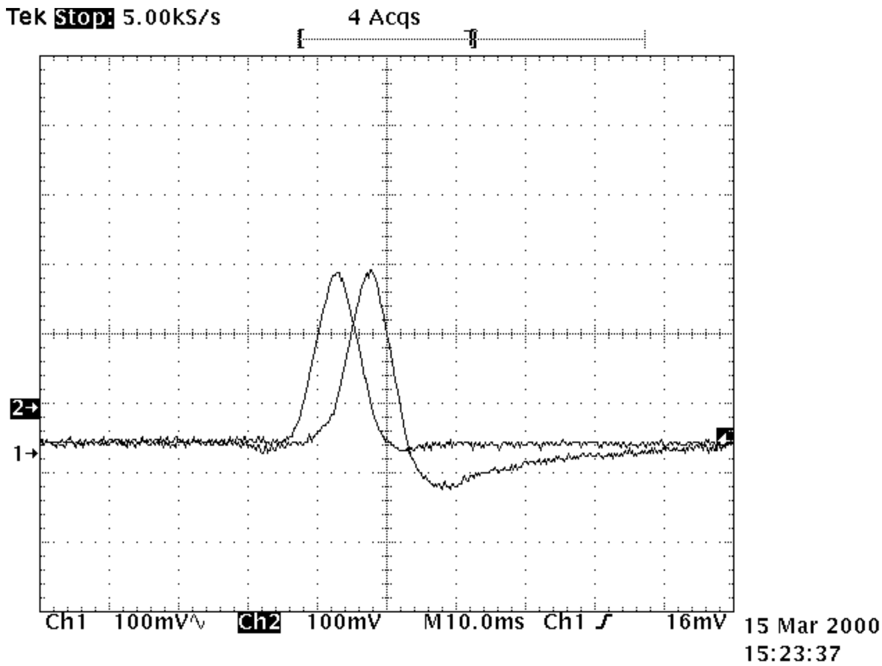
The effective degree of freedom is:

$$\nu_{\mathrm{eff}} = \frac{u_{\mathrm{c}}^4}{\sum_{i=1}^{18} \frac{u_i^4}{\nu_i}}$$

For different measuring length, the calculated effective degree of freedom is different. When measuring length dL is small, we have effective degree of freedom of 83. When measuring length dL increased, the effective freedom increased too. When dL□280mm, the effective degree of freedom is =93. Therefore we set the effective degree of freedom as 83 for all measuring length. For 95% confident level, we can get k = 2. Therefore the expanded uncertainty is:

$$U_{95} = 2\times u_{\mathrm{c}} = 2\times 53 \text{ nm} = 106 \text{ nm} \approx 0.11\ \mu\text{ m}$$

The image of following is the detected signals of optical-electronic microscope in line position. Two signals are due to dual slits. Moving speed of table is 1.282 mm/s.



B) Tabular description of the measurement methods and instruments: NIM

Line detection

Parameters	Parameters used for the measurement
Microscope type:	dynamic optical-electronic microscope
Light source	white light
Wavelength(s)	-
Slit length	can adjust, using 6µm when measuring
Slit width	0.3 mm
Polarization	-
Coherence	-
Aperture/magnification	NA=0.2□magnification□80x
Detection mode	optical-electronic microscope
Detection principle	dynamic, dual slits
Detection velocity	-
Sampling frequency (image/interferometer)	synchronous reading of signal and interferometer
Edge detection criterion	The equal point of two signals from dual slit
Edge detection short term repeatability (1s)	42 nm

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands(k=1)
Interferometer light source / wavelength	633 nm He-Ne	1.15×10^{-8}
Resolution of displac. Interferometer	80 nm	23 nm
Interferometer medium	□□	
Refractive index:		
=>refractometer:		
=>Edlen´s formula:		1×10^{-8}
Air temperature	20±0.5℃	0.0115°C
Air pressure		15 Pa
Air humidity		23.09 Pa
CO_2-content	444×10^{-6}	60×10^{-6}
Guide error	$\pm 1.0\times10^{-5}$	5.8×10^{-6}
Abbe offset	± 1 mm	0.1 mm
Alignment error:		
Interferometer	$\pm 2.5\times10^{-5}$	1.44×10^{-5}
Scale	$\pm 2.0\times10^{-5}$	1.16×10^{-5}

OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands(k=1)
Scale temperature	20±0.5℃	0.0116 °C
Number of repeat measurements in one scale position	72	
Number of scale orientations	36	
kind of support	Line contact, four supportsp in bessel position of scale	
clean room class	Normal laboratory for dim. measurement	

Measurand 1B: Deviations from nominal length for every 5 mm line, Zerodur: NIM

Uncertainty of measurement

name and symbol x_I	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Resolution of inteferometer $\boldsymbol{N}$	R	0.289	∞	λ_0 /8	23 nm
Wavelength of light source used for displacement measurement λ_0	R	$1.15\times10^{-8}\lambda_0$	50	dL /λ_0	1.15×10^{-8} dL
Index of refraction of air n_N	N	1×10^{-8}	12.5	dL	1×10^{-8} dL
Air Temperature t_{air}	R	0.0115 °C	12.5	0.930×10^{-6} dL °C^{-1}	1.07×10^{-8} dL
Air Humidity RH$_{air}$	R	23.09 Pa	12.5	0.371×10^{-9} dL Pa^{-1}	0.86×10^{-8} dL
Air CO_2 concentration c_{co2}	N	60×10^{-6}	6500	1.45×10^{-4} dL	0.87×10^{-8} dL
Air Pressure p_{air}	R	15 Pa	12.5	2.683×10^{-9} dL Pa^{-1}	4.03×10^{-8} dL
Linear coefficient of thermal expansion of scale material α	N	1.55×10^{-8} °C^{-1}	50	0.1°C × dL	0.155×10^{-8} dL
Scale temperature Δt_s	R	0.0116 °C	12.5	5.5×10^{-7} dL °C^{-1}	0.348×10^{-9} dL
Diameter of diaphragm for incidence light a	R	0.0116 mm	50	1×10^{-7} dL mm^{-1}	0.116×10^{-8}dL
Repeatability of edge detection S$_E$	N	0.52	39	λ_0 /8	42 nm
Microscope axis alignment δ_{Ealig}	R	12 nm	12.5	1	12 nm
Cosine errors of interferometer alignment δl_{li}	R	3.6×10^{-10} dL	12.5	1	3.6×10^{-10} dL
Errors of scale alignment δl_{Si}	R	2.4×10^{-10} dL	12.5	1	2.4×10^{-10} dL
Interferometer deadpath influences δl_{DP}	R	4 nm	2	1	4 nm
Interferometer resolution δl_{Res}	R	3 nm	∞	1	3 nm
Errors due to Abbe offsets and pitch and yaw of translation stages δl_{ai}	R	6 nm	12.5	1	6 nm
Interferometer nonlinearity δl_{NL}	R	12 nm	12.5	1	12 nm

Formula or expression of uncertainty shall be given in the same way as for MRA C:

$$u_{\mathrm{c}}(dl) = \sqrt{\sum_{i=1}^{18} u_i^2} = \sqrt{(51.4\ \mathrm{nm})^2 + (4.65 \times 10^{-8}\ \mathrm{d}L)^2}$$

$$\nu_{\mathrm{eff}}(dl) = \frac{u_{\mathrm{c}}^4}{\sum_{i=1}^{18} \frac{u_i^4}{\nu_i}}$$

Combined standard uncertainty: $u_c(dl)$ =53 nm

Effective degree of freedom: $\nu_{\mathrm{eff}}(dl)$ =84

Expanded uncertainty: $U_{95}(dl)$ =106 nm

MIKES: Measurement report

A) Description of the measurement methods and instruments

MIKES‘ line scale interferometer uses a dynamic method of measurement with a moving microscope for speed, simplicity, and considerations of space requirements. The graduation line distances are measured during continuous motion, which makes the system fast and the interferometer insensitive to minor turbulence in the interferometer beam path. Possible problems with speed fluctuations and time delay in observing the lines are avoided by using an electrically shuttered CCD camera as a line detector and synchronous data sampling. Each image of the CCD camera consists of two fields charged in 1 ms and with time separation of 20 ms. The interferometer is constructed on a vibration isolated stone table to eliminate mechanical disturbances. The microscope is fixed on one side of a carriage and the CCD camera on the top of the microscope, axis of which is adjusted perpendicularly to the scale plane.

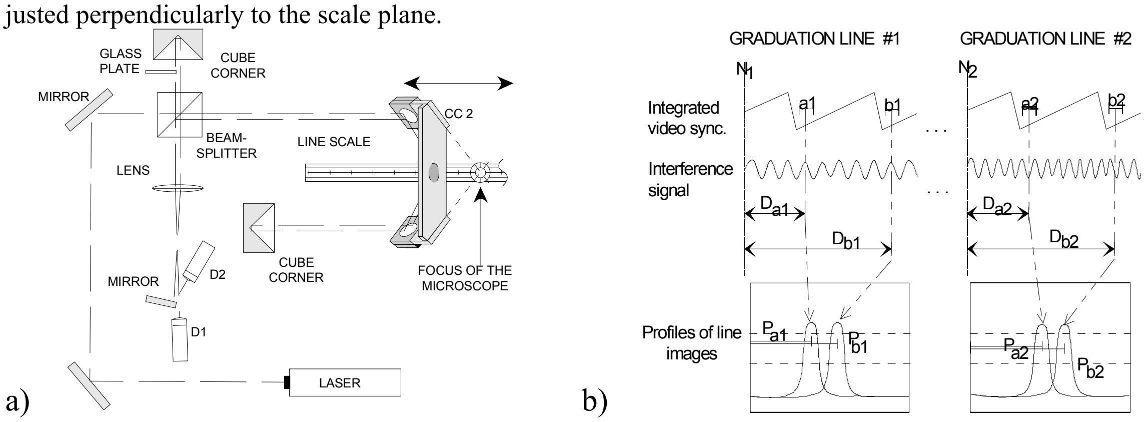


Figure 1. a) Optics of the line scale interferometer. b) Analysis of the measurement data.

Abbé error is eliminated with a large cube corner (CC2, figure 2 a), making it possible to adjust the focus point of the microscope and the apex of the cube corner to the same point. This cube corner is constructed from three separate round mirrors adjusted to angles of 90° with each other. Ideal adjustment of the focus point and the apex of the cube corner nearly completely eliminates the Abbé error. The displacement of the microscope is followed by a Michelson interferometer utilising a calibrated 633 nm Zeeman-stabilised He-Ne laser. The interference fringes are detected by two detectors D1 and D2 and counted by a direction-sensitive quadrature counter.

In measurement run, the carriage moves in one direction while the programme continuously monitors the counter reading. When the carriage is approaching a line, the programme slows down the speed of the carriage and just before passing over the line it stores the current counter reading (Ni, Ni; figure 2 b), starting a synchronized sampling. In the sampling, one interference signal and an integrated video synchronisation signal, for determination of the field forming positions (ai, bi), are digitised, the graduation line image is stored, and the refractive index and temperature of the scale are calculated and stored. This set of samples is taken for each line after which a new run is started in the opposite direction. A single measurement of the decimetre lines of a 1 m scale takes approximately 15 minutes. The first approximation for the measured length is calculated as the distance between the positions where the graduation line fields are formed (Ni-Dij).

Average profiles of the graduation lines are formed by summing picture element intensities of each row of the CCD. Thereafter, the centre points of the graduation lines (Pa1, Pa2, Pb1, Pb2) are determined from the slopes of the line profile and a correction term needed to superimpose the centre points is applied. The refractive index of air is determined by Edlen’s formula updated by Bönsch et al. The line scale interferometer is capable of calibrating line separations from 10 µm to 1 m of good quality line standards, having line widths from 2 to 50 µm.

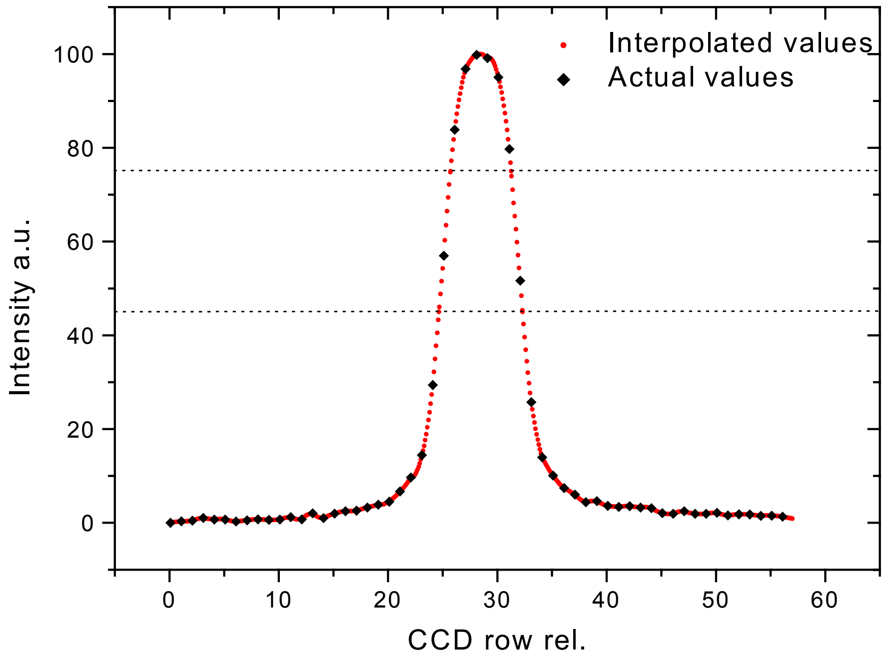


Fig. 2. Profile of 0 line of the quartz line scale taken during measurement. Profile centres were calculated as weighted mean of values between 45% and 75% intensity levels.

Refs.: A. Lassila, E. Ikonen, and K. Riski, Interferometer for calibration of graduated line scales with a moving ccd camera as a line detector, Applied Optics 1994, 33, 3600-3603.
A. Lassila, E. Ikonen and K. Riski, Interferometers for calibration of length standards, Optical Engineering, 1995, 34, 2619-2622.

B) Tabular description of the measurement methods and instruments: MIKES

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Optical, Wild M3Z mono with ccd camera Sony XC-73
Light source	Coaxial illumination by light via fibre from halogen light source
Wavelength(s)	Halogen light filtered by cold filter
Slit length	100 µm
Slit width	50 µm
Polarization	Non-polarised
Coherence	White light
Aperture/magnification	25 + 10:1
Detection mode	Line centre is calculated from digitised video image
Detection principle	Line centre calculated as weighted mean from intensity profile of a line
Detection velocity	~0.2 mm/s
Sampling frequency (image/interferometer)	1 image (with even and odd field) is charged (charg. time 1 ms) from each line, simultan. interference and video sync. signal are digitised (20 kHz)
Edge detection criterion	Centre is calculated as weighted mean of line profile between 45-80% intensity levels
Edge detection short term repeatability (1s)	10 nm (line centre detection)

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Interferometer light source / wavelength	Zeeman stabilized He-Ne 633 nm	2 Mhz
Resolution of displac. Interferometer	< 1 nm	
Interferometer medium	Air	
Refractive index:		
=> refractometer:		
=> Edlen´s formula:	X	$1x10^{-8}$
Air temperature	4 pt100 sens. & Systemteknik 1228, 20±0.05	15 mK
Air pressure	Vaisala PTB200A, ambient	5 Pa
Air humidity	Vaisala HMI 36 & 2xHMP35B, 35-50%	0.2 K
CO_2-content	400 ppm	50 ppm
Guide error	±3 µrad	1 µrad
Abbe offset	2 mm	1 mm
Alignment error:		
Interferometer	< 20 µrad	
Scale	< 10 µrad	

Other measurement conditions

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	20	5 mk
Number of repeat measure ments in one scale position	2 (includes 5 separate runs)	
Number of scale orient.	2	
kind of support	Support from Airy points by Teflon supports	
clean room class	NA	

Measurand 1B: Deviations from nominal length for every 5 mm line. Zerodur: MIKES

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
repeatability ie. video noise etc. (all type A components), s	Std.	7 nm	19	1	7.0
Influence of line edge detection algorithm. possible asymmetry of line profiles. line shape, δ_{Ealg}	Std.	5 nm	4	1	5.0
Error due to Abbe offsets and pitch and yaw, δl_{Ai}	Rect.	6 µrad (over 0.3 m x&y)	4	$(2*(0.002^2\sin^2(xi)))^{½}$ / 2√3 L/0.3 m	16.3 L
Diffraction effect of the laser beam, δl_{dif}	Rect.	8 nm	2	L	8.0 L
Scale temperature difference from 20, Δt_s	Std.	10 mK	2	$3x10^{-8}L$ m/K	0.3 L
Linear coefficient of thermal expansion, $\alpha_{Z.\ Cr}$	Std.	0.02 µ 1/K	1	0.02 L Km	0.4 L
Vacuum wavelength of laser. λ_o	Std.	2.7 fm	100	L	4.0 L
Index of refraction of air (equation), n_{air}	Std.	$1x10^{-8}$	100	L m	10.0 L
Air temperature, t_{air}	Std.	15 mK	4	$9.6x10^{-7}$ L m/K	14.4 L
Air pressure, p_{air}	Std.	5 Pa	4	$2.7x10^{-9}$ L m/Pa	13.5 L
Dew point, D_{air}	Std.	0.2 K	4	$3x10^{-8}$ L m/K	6.0 L
Air CO_2 concentration, c_{CO2}	Std.	50 ppm	4	$1.5x10^{-10}$ L m/ppm	7.5 L
Flattness deviation of the scale surface & microscope axis alignment, δh	Std.	8 nm (over 0,3 m)	3	1 $L/0,3$ m	26.7 L
Errors of scale alignment & cosine error, δl_{Si}. δl_{Ii}	Rect.	20 µrad	4	$x_i^2/2$ L m/rad	0.02 L
Linear coefficient of compressibility, K	Std.	600 Pa	4	$-5.8x10^{-7}$ L m/bar	3.5 L

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(L)$= Q[8.6; 40.6L] nm, L in metres, Q[x; y]=$(x^2+y^2)^{½}$

Effective degree of freedom: $\nu_{eff}(L)$= V[19; 13L], L in metres

V[x; y]=$u_c(L)^4/(8.6^4/x+(40.6L)^4/y)$

Expanded uncertainty: $U_{95}(L)$= Q[17.7; 83.6L] nm, L in metres (k=2.06)

⇨ u_c(5 mm)= 8.6 nm (k=1); ν_{eff}(5 mm)= 19;

u_c(280 mm)= 14.3 nm (k=1); ν_{eff}(280 mm)= 27;

SP: Measurement report

A) Description of the measurement methods and instruments

The scales have been measured in 1-D measuring bench with a total length of three meters (ULMM 3000). Scale lines where detected using a photoelectric microscope (Leitz Wetzlar Messtubus 2), mounted on the moving wagon of the measuring bench. A laser interferometer (HP 5528 A) was used to measure the displacement of the microscope. ....

Scale support: During measurement the scales were resting on two supports at the specified marks, one roll with ball bearings and one sharp edge. Both supports could easily be adjusted in order to align the scales. ....

Measuring bench: The translation stage (TS) of the bench consists of two parts. The main part is sliding (i.e. rolling) on the bench and is used to coarsely move the microscope into position. The second part of the TS (which is mounted on the main part) is used for fine-setting the microscope to a line. For shorter scales (in this comparison the 0,46 mm test-structures) only the fine-setting part is used. Everything is operated manually. ....

Measurement procedure: The 0,46 mm test-structures were measured using only the fine-translation part of the TS (see discussion below). Both the main scales and the 4,6 mm test-structures where measured by coarsely move the microscope to each scale line (using the main part of the TS) and then fine-tune with the second part of the TS.

Since the instrument is manually operated, the measurements are rather time-consuming. In order to control the induced drift (temperature, deadpath etc.) the microscope was moved back to the zero-line after every 10 lines measured. ....

Notes on some effects contributing to the uncertainty: Some “mechanic” effects contribute significantly to the overall uncertainty. 1) Due to the rather large weight of the moving wagon (with the microscope) any movement will cause the whole measuring bench to bend, which effectively will cause the scale to move relative to the laser interferometer (which is placed on a separate stand). How big this “movement” is depends on where on the bench the scale is placed. This effect is linearly corrected for but there will still be a remaining length-dependent uncertainty (error).

2) Tilting of the microscope due to coarse movement of the wagon is caused by a combination of bending of the bench, imperfect straightness of the measuring bench and possibly also form errors in the roller bearings on which the wagon is moving. 3) On a shorter scale some tilting is caused by the fine-translation part. ....

SCALE TEMPERATURE: IN COMPARISON TO OTHER UNCERTAINTIES, THE TEMPERATURE DEVIATION FROM 20 °C (MAX ±0,10°C) IS NEGLIGIBLE FOR THE ZERODUR SCALE. FOR THE QUARTZ SCALE, CORRECTIONS HAVE BEEN MADE AND THE UNCERTAINTY IS CONSIDERED.

Combined uncertainty: Since both scales (quartz and Zerodur) seemed to have equally fine lines (quality) and were measured using similar measuring procedures, the combined measuring uncertainty is the same for both scales. There is however a difference between the 0,46 mm structures and the longer ones (4,6 mm and 280 mm), based on the repeatability and a slightly different measuring procedure. ....

....

B) Tabular description of the measurement methods and instruments: SP

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Leitz Wetzlar Messtubus 2
Light source	*Standard white light lamp*
Wavelength(s)	*White*
Slit length	*100 µm*
Slit width	*4 µm (sweep during measuremenst 8-16 µm, 470 Hz)*
Polarization	
Coherence	
Aperture/magnification	*5x*
Detection mode	*Reflecting lines, centre position*
Detection principle	*Fotoelectric*
Detection velocity	
Sampling frequency (image/interferometer)	
Edge detection criterion	*Intensity (manually set)*
Edge detection short term repeatability (1s)	*0,02 µm/2 µm lines, 0,04 µm/4 µm lines*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty (1s) for measurands
Interferometer light source / wavelength	*HeNe 633 nm (vacuum)*	$3\cdot10^{-9}$ (relative)
Resolution of displac. Interferometer	*0,01 µm*	
Interferometer medium	*Air*	
Refractive index:		
=> refractometer:		
=> Edlen´s formula:	*Yes*	$1\cdot10^{-8}$
Air temperature	*19,9*	*0,09 K*
Air pressure	*1000 hPa*	*29 Pa*
Air humidity	*50 %*	*3 %*
CO_2-content	*500 ppm*	*120 ppm*
Guide error		
Abbe offset		
Alignment error:		
Interferometer	*Max ±0,6 mm/3000 mm = 200 µrad*	*120 µrad*
Scale	*Max ±0,05 mm/300 mm = 170 µrad*	*100 µrad*

OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	*19,95 ± 0,10 °C*	*0,06 K (sensors not directly applied)*
Number of repeat measurements in one scale position	*1 (3-5 measurement series)*	
Number of scale orientations	*2*	
kind of support	*Edge/roll*	
clean room class		

Measurand 1B: Deviations from nominal length for every 10 mm line, Zerodur: SP

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Inteferometer wavelength λ_0	R	$3{\cdot}10^{-9}$	>100	L	$3{\cdot}10^{-9}$L
Index of refraction of air, n_{air}	N	$1{\cdot}10^{-8}$	>100	L	$1{\cdot}10^{-8}$L
Air temperature, t_{air}	R	0,09 K	>100	$9{,}5{\cdot}10^{-7}$L	$9{\cdot}10^{-8}$L
Air pressure, p_{air}	R	29 Pa	>100	$2{,}7{\cdot}10^{-9}$L	$8{\cdot}10^{-8}$L
Air humidity, RH_{air}	R	3 %	>100	$8{,}5{\cdot}10^{-7}$L	$3{\cdot}10^{-8}$L
Air CO_2 *content,* C_{co2}	R	120 ppm	>100	$1{,}3{\cdot}10^{-10}$L	$2{\cdot}10^{-8}$L
Rounding of refractive index in laser interferometer, R_{air}	R	$3{\cdot}10^{-8}$	>100	L	$3{\cdot}10^{-8}$L
Interferometer alignment, δl_{Ii}	R	120 µrad	>100		$1{\cdot}10^{-8}$L
Scale alignment, δl_{Si}	R	100 µrad	>100		$1{\cdot}10^{-8}$L
Movement of scale due to bending, M_{Sc}	R	$2{,}1{\cdot}10^{-7}$	10	L	$2{,}1{\cdot}10^{-7}$L
Abbe error 1(bending and straightness dev of rail), δl_{Ai1}	R	$2{,}5{\cdot}10^{-7}$	10	L	$2{,}5{\cdot}10^{-7}$L
Abbe error 2 (variations shorter then approx.10 mm), δl_{Ai2} *	R	70 nm	10	1	70 nm
*Overall repeatability R (pooled from 2x5 series, results as the mean of 5 meas.series)**	N	70 nm	8	1	70 nm
Interferometer resolution, δl_{Res}	R	6 nm	>100	1	6 nm
Non-linearity of drift (incl. deadpath error), δl_{Drift} *	R	50 nm	20	1	50 nm
Res. of edge detection, δ_{Eres} *	R	30 nm	10	1	30 nm

* Only valid for the 4,6 mm and 280 mm scales (line widths 4 µm). For the 0,46 mm scale see separate sheet.

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(dl)$ = Q [115; 0.35L] nm, L in mm

Effective degree of freedom: $\nu_{eff}(dl)$ = from 30 up to 56

Expanded uncertainty: $U_{95}(dl)$= Q [242 nm; 0.74L] nm, L in mm (k = 2,1)

IMGC: Measurement report

A) Description of the measurement methods and instruments

The measuring apparatus is based on a Moore Measuring Machine, modified at IMGC, equipped with a laser interferometer and a optical probe. This latter consists of a optical microscope with a CCD-camera. The measuring apparatus is that one which is normally used for calibrating larger rings and plugs when equipped with a LVDT mechanical probe.

Tab. 1. Instrument identification.

Instrument	**Manufacturer**	**5 MODEL**	**Ser. No.**
Universal Measuring Machine	Moore	n. 3	M245
Laser interferometer	HP	5518	3626A03700
Microscope	Nikon	OPTIPHOT 100S	628562
Objective	Leitz	∞/0 Plan 125X N.A. 0,80	
CCD camera	REGIS	T1RS4NL	30AGAF00192
Stage micrometer	Leitz	-	060_643.008

Measurement procedure

By IMGC, this exercise is considered a pilot study on the subject of wide range linescale calibration (this range being out of the IMGC calibration services).

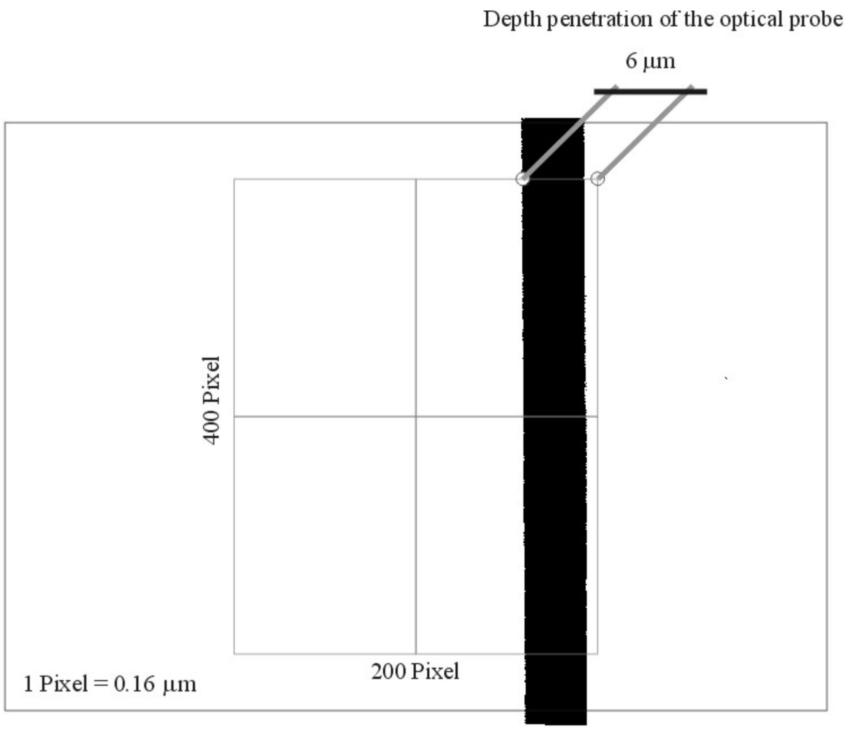
The optical probe has been developed for the calibration of line standards, i.e. bi-dimensional artefacts with a high definition of the measured edge.
A rectangular window is created via software in order to simulate the behaviour of a mechanical probe. The “contact” reading is obtained from a digital image processing system (assembled at IMGC with boards manufactured by Imaging Technology) of the CCD-camera output of the Nikon microscope.

The window width corresponds to the ball tip diameter for bi-directional measurements, whereas the window height determines the number of pixel rows activated (integration amplitude). By displacing the artefact (relative displacement between artefact and CCD camera), the window “penetrates” in the measurement area and defines the artefact edge position by measuring its distance from the window side (left or right, see Fig.1).

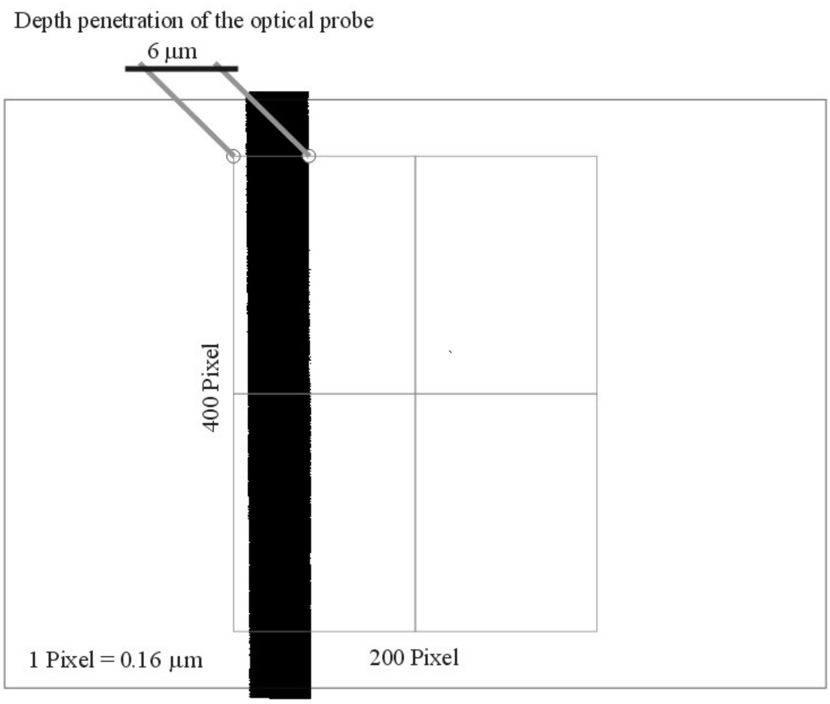
In the measurement procedure the optical probe is used to determine the edge positions at the left- and right-sides of the line for the interferometric displacement measurements. Then, the centre position of the line is determined from the edge positions.
The inverse of window sensitivity (about 0.16 µm/pixel, with a magnification of 125X) is determined on both window sides against the displacements (between 5 µm and 6 µm) measured with the laser interferometer, when the window penetrates the measured line from the left- and right-sides.

With this optical probe, the measurement procedure and data processing are exactly the same used with the mechanical probe, except for the probe calibration which is made against the interferometer itself.

Traceability is given by the wavelength of the laser interferometer.



Left side contact



Right side contact

Fig. 1 - 2D image of CCD sensor

The Fig. 1 describes the way the position of the line was deduced from the 2D CCD image signal. It gives a typical image data of the scale lines (not of the line „0“).

Measurement setup

The equipment configuration from bottom up was: Moore carriage, vertical stage (height adapter up to Abbe condition in vertical), tilt and rotary stages, base support designed for the Airy support points of the linescale, linescale.

The applied procedure is the following:

The linescale is placed on the base support and is aligned (visually) with the displacement axis and the measuring (laser) axis. The alignment is further improved by checking the focus and position of the line end on the video frame while displacing the artefact from the line „0“ up to the line „280“. To optimize the alignment the procedure is usually repeated several times for each scale to be measured.

With the automatic control of the Moore machine, no manual handling of the linescale is required to reset the equipment between each set of measurements.

The positions of the lines are then measured at the central section of the lines with a CCD image window length of about 64 µm. With the zerodur main graduation, measurement runs have been taken also with a little offset (positive and negative) from the central section of the lines because the window length is smaller than 100µm as given in the measurement protocol.

The adopted measurement strategy is:
1. The total length over 280 mm (30 runs for zerodur linescale, 15 runs for quartz linescale);
2. Every 5 mm line over 280 mm (10 runs for zerodur linescale, 11 runs for quartz linescale);
3. Every 1mm line over first 20 mm (15 runs for zerodur linescale, 14 runs for quartz linescale);
4. Every 100 µm line over 4,6 mm length (5 runs zerodur linescale).

For each run the deviation from the nominal length is obtained from the average of forward and backward measurements of the line positions.

B) Tabular description of the measurement methods and instruments: IMGC

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Nikon Optiphot 100S / Objective Leitz ∞/0 Plan 125X N.A. 0,80
Light source	*Halogen lamp - Illuminator Intralux 4000*
Wavelength(s)	*White light*
window length	*64 µm*
window width	*32 µm*
Polarization	---
Coherence	---
Aperture/magnification	*0,80 / 125X*
Detection mode	*Image processing of the 2D CCD image video frame*
Detection principle	*Left- and right-dide line edge detection to calculate the centre line position*
Detection velocity	
Sampling frequency (image/interferometer)	*25 frames/second; synchroneous reading of signal and interferometer*
Edge detection criterion	*50 % level dark-white light intensity*
Edge detection short term repeatability (1s)	*4 nm*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Interferometer light source / wavelength	Stabilized He-Ne laser / 633 nm	$7 \cdot 10^{-9} \cdot L$
Resolution of displac. Interferometer	10 nm	2,9 nm
Interferometer medium	Ambient air	
Refractive index:	calculated from ambient air parameters	$2{,}3 \cdot 10^{-8} \cdot L$
=> refractometer:		
=> Edlen´s formula:	revised Edlen's Formula	
Air temperature	20±0,1°C, precision thermometer	
Air pressure	~ 100 kPa, Rosemount barometer	
Air humidity	~ 50%, Mitchell igrometer	
CO_2-content	Assumed to be 400 ppm	
Guide error	40 µrad	
Abbe offset	0,5 mm	7 nm
Alignment error:		
Interferometer		$5 \cdot 10^{-8} \cdot L$
Scale		$2{,}6 \cdot 10^{-8} \cdot L$

OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature		$3{,}9 \cdot 10^{-10} \cdot L$
Number of repeat measurements in one scale position	*As given above in the poaragraph A)*	
Number of scale orientations	*1*	
kind of support	*Airy support base*	
clean room class	*Not classified – laboratory with filtered air*	

Measurand 1B: Deviations from nominal length for every 5 mm line, Zerodur: IMGC

UNCERTAINTY OF MEASUREMENT

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
edge detection repeatability	N	40 nm	20	1	40
interferometer digital resolution	R	2,9 nm	100	-	2,9
vacuum wavelength	N		100	1	$7\cdot10^{-9}\cdot L$
air refractive index	N		100	1	$2{,}3\cdot10^{-8}\cdot L$
interferometer non-linearity	R	1 nm	50	-	1
interferometer deadpath	R	2,4 nm	100	-	2,4
linear coefficient of thermal expansion (α) of scale	N	$2\cdot10^{-8}$ K^{-1}	50	$(t_s - 20)\cdot L$	$2\cdot10^{-9}\cdot L$
difference of the scale temperature from the reference temperature during measurement	N	0,013 K	50	$\alpha\cdot L$	$3{,}9\cdot10^{-10}\cdot L$
linear coefficient of compressibility (k) of the scale material	N	10^{-12} Pa^{-1}	50	$(101325 - p)\ L$	$1\cdot10^{-9}\cdot L$
variations of air pressure during measurement	N	1 kPa	50	$k\cdot L$	$5{,}8\cdot10^{-9}\cdot L$
Abbe offsets and pitch and yaw of translation stages	R	7nm	100	-	7
Imperfect alignment of scale (laser) with respect to meas. direction	R		100	-	$5\cdot10^{-8}\cdot L$
imperfect alignment in direction and height of the linescale	R		15	-	$2{,}6\cdot10^{-8}\cdot L$
Microscope axis alignment and straightness of translation stage	R	28 nm	10	-	28

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(dl)$ = 52 nm
Effective degree of freedom: $\nu_{eff}(dl)$ = 43

Expanded uncertainty: $U_{95}(dl)$ = 108 nm

VNIIM: Measurement report

A) Description of the measurement methods and instruments

An optical scheme of the comparator (Fig.1) consists of a laser polarization interferometer, a refractometer and a confocal microscope. Parts of the laser interferometer and refractometer are fixed on a granite base. A carriage is moved over teflon supports at a distance of 1 m. As the carriage moves its rotation is not greater than 5 μrad Two reflectors of the interferometer and the confocal microscope are mounted on the carriage. The microscope focus is located on the measurement axis of the inteferometer.

In the microscope there are a laser diode with a wave length of 540 nm and an objective with an aperture of 0.9 An illuminator of the microscope forms an illuminated strip with a width of 1μm. Light is reflected and forms the image in a plane of a slot. The width of the slot corresponds to 0.3 μm (in the plane of a scale), the length is 100 μm. A signal from the photodiode is put into a computer.

One of the two modes (Δ = 640 MHz) of the stabilized He/Ne laser of the 1 mWatt power is used in the interferometer, the second one is applied in the refractometer. A refractive index is measured in the process of filling a chamber of 1 m in length with air. Both the refractometer and interferometer have two photo diodes providing to shape the signals with a phase shift of 90^0.

The scale is located on two piezo-supports. Focusing is controlled by a signal from the microscope. The measurement zone is closed by a thermal screen. Alongside the scale a platinum thermometer (10 Ohm) is located. The difference between the temperature of the scale and that of the platinum thermometer is measured with a set of differential thermocouples. The temperature inside a room is kept at a level of 20±0.1 ^{0}C.

Output signals of the photo-detectors of the laser interferometer, refractometer and microscope enter the computer that is equipped with an analogue-to-digital converter with a multiplexing unit at its input. The word size (word length) of the converter is 12 bits, the frequency of conversion is 100 kHz.

A phase of the interference signal is calculated as *arctg* of the ratio of the signals of two photodetectors. Parameters of the input signals are corrected after each period of the interference signal. The coordinates of the scale graduation line centers are calculated at the time of joint processing of the microscope and interferometer signals. A center of gravity is calculated for that part of the graduation line profile, which is situated between the levels of 25 and 40 % of a maximum level of the signal (Fig. 2).

Measurements are done in a dynamic mode. To control the carriage electric motor a digital-to-analogue converter is used. When the microscope is moving over the graduation line the speed of the carriage is decreased (0.05 mm/s). Fig. 2 shows the microscope signal at the time when the carriage is moving over the zero graduation line of the quartz scale. Along the abscissa axis the coordinate of the carriage is expressed in μm, along the coordinate axis the microscope signal is shown.

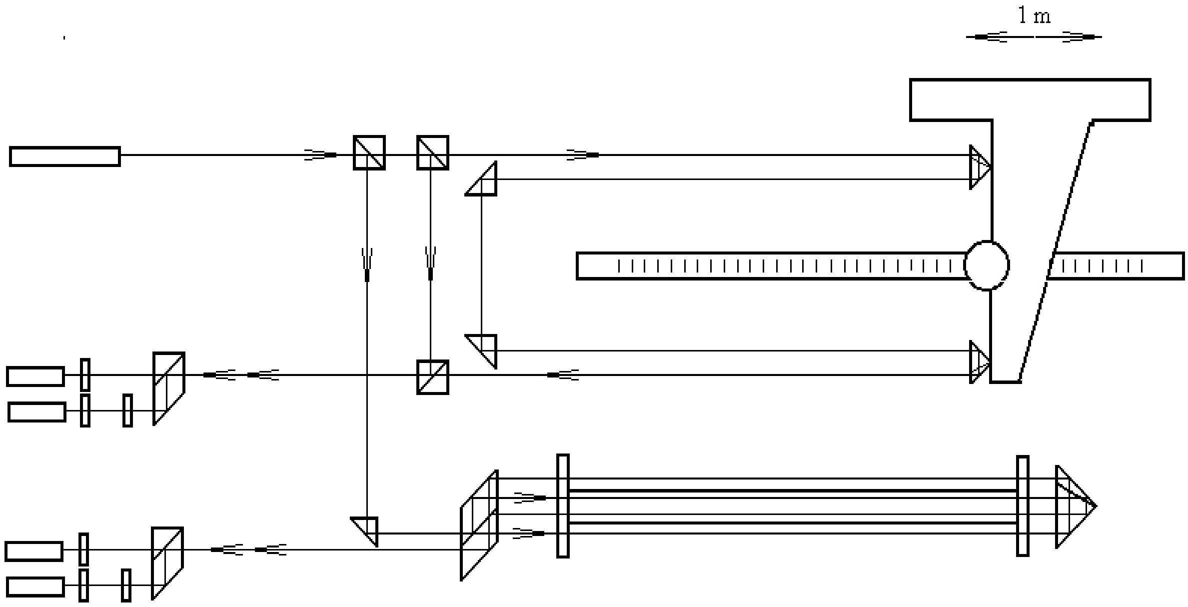


Fig.1 Optical scheme of comparator.

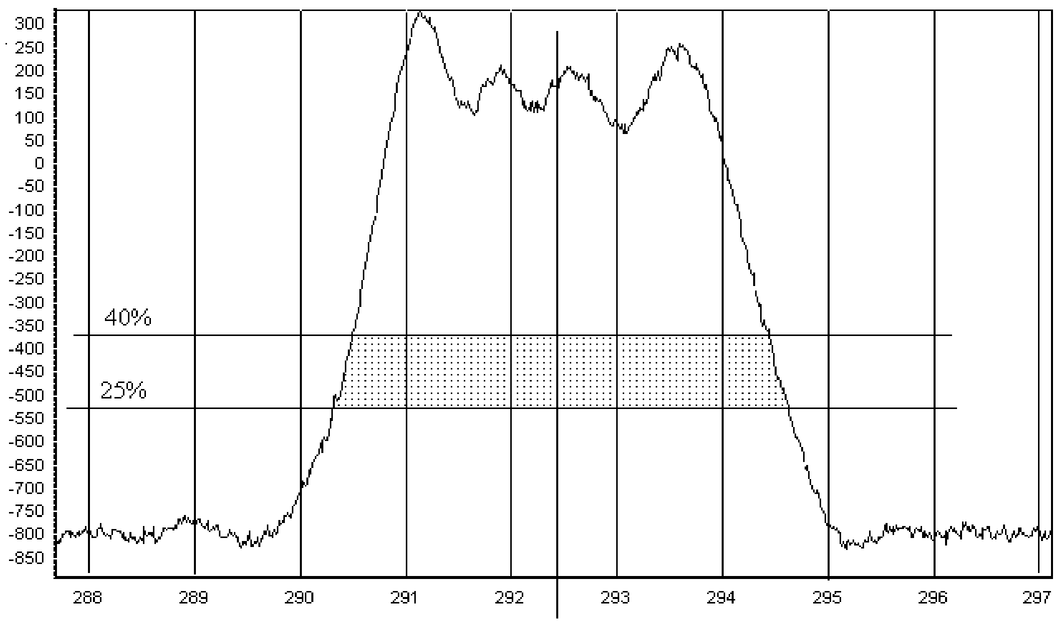


Fig. 2 Microscope signal when it is passing over the zero graduation line of the quartz scale.

B) Tabular description of the measurement methods and instruments: VNIIM

Line detection

Parameters	Parameters used for the measurement
Microscope type:	confocal with the slot diaphragm
Light source	LASER DIODE
Wavelength(s)	635 nm
Slit length	100 µm (in the scale plane)
Slit width	0.3 µm (in the scale plane)
Polarization	circular
Coherence	100%
Aperture/magnification	0.9 / 80
Detection mode	Photo- diode
Detection principle	At the time when the carriage is moving the signals of the microscope and interferometer are registered in synchronism
Detection velocity	0.05 mm/s
Sampling frequency (image/interferometer)	The microscope signal is read off in synchronism with the interferometer signal at the frequency of 30 kHz
Edge detection criterion	The center of gravity is calculated for that part of the graduation line profile which is situated between the 25 and 40% of the maximum level.
Edge detection repeat. (1s)	

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Interferometer light source / wavelength	Stabilized He/Ne laser with the wave length of 630 nm	2E-8 L
Resol. of displacement of the interferometer	0,1 nm	
Interferometer medium	Air	
Refractive index:		
=> refractometer:	3E-8	3E-8 L
=> Edlen´s formula:		
Air temperature		
Air pressure		
Air humidity		
CO_2-content		
Guide error	1 µm, 5 µrad	
Abbe offset	0.1 mm	0.5
Alignment error:		
Interferometer	0.1 mrad	5E-9 L
Scale	0.02 mrad	6E-10 L

OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurand
Scale temperature	20±0.1 K (0.005 K)	
Number of repeat measure ments in one scale position	5	
Number of scale orientation	2 (AB/BA)	

Measurand 1B: Deviations from nominal length for every 5 mm line, Zerodur: VNIIM

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Length independent:					
Sc Centre line positions reproduction	N	2nm	13	1	2 (*)
δ_{Efoc} Influence of focal length variation	N	1 µm	5	0.002 (**)	2
δ_{Ealig} Microscope axis alignment	R	1 mrad	>100	δ_{Estr}	1
δl_{Res} Interferometer resolution	N	0.1nm	5	1	0.1
δl_{NL} Interferometer nonlinearity	N	3nm	5	0.3 (***)	0.9
δl_{Ai} Errors due to Abbe offsets and pitch and yaw of translation stages	R	0.1 mm	>100	δ_{Erot}	0.5
Length dependent:					
λ_o vacuum wavelength of light source used for displacement measurement	N	2E-8	10	L	2E-8* L
n_{air} Index of refraction of air	N	5E-8	10	L	5E-8 *L
δl_{Ii} Cosine errors of interferometer alignment	R	0.1 mrad	>100	$(\delta l_{Ii}/2)$*L	5E-9* L
δl_{Si} Errors of scale alignment	R	0.02 mrad	>100	$(\delta l_{Si}/2)$*L	4E-10*L
, α_Z Linear coefficient of thermal expansion of scale material	N	3E-8 K^{-1}	10	$(t_s - 20)$ * L	3E-9*L
$\Delta t_s = (t_s - 20)$ is the difference of the scale temperature t_s in °C during the measurement from the reference temperature of 20 °C	N	0.005 K	10	$\alpha_{Z,}$ * L	2.8E-9*L

$\alpha_{Z,}$	$3\cdot10^{-8}$ K^{-1} ($U\alpha = 4\cdot10^{-8}$ K^{-1})
$(t_s - 20)$	±0.1 K

guide error:

δ_{Estr} straightness	1 µm
δ_{Erot} carriage rotations	5E-6 rad

Notes:

(*) To detect (for determination of) the defect lines, the experimental standard deviations of the mean value for all intervals given in the Appendix, Fig.4

(**) Expert evaluation (estimation)

(***) Influence of the non-linearity decreases due to averaging at the edges of the line

Combined standard uncertainty: $u_c(dl)$ = 3.2 + 4.4 E-8*L nm (from 3.2 nm to 15.6 nm)

Effective degree of freedom: $\nu_{eff}(dl)$ = 13

Expanded uncertainty: $U_{95}(dl)$ = 7 + 10 E-8*L nm (from 7 nm to 35 nm)

NMIJ: Measurement report

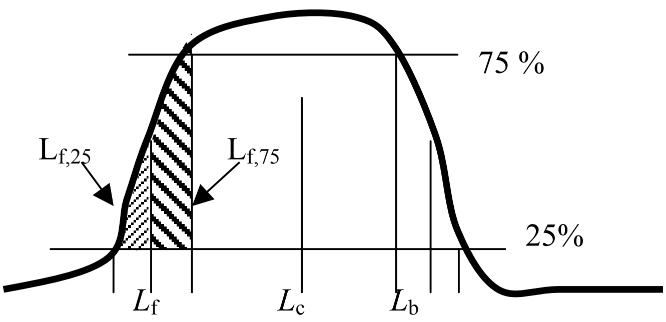
A) Description of the measurement methods and instruments

1. Principle

Line standards are calibrated by a line standard interferometer with a He-Ne laser as a light source, wavelength of which is calibrated by an I_2 stabilized He-Ne laser.

2. Method

A line standard is set on two supports connected on a moving stage floated by air. The moving stage is translated for the line standard movement by a motor. Then, the displacement of the stage is measured by an interferometer while the graduation signal through a slit is detected by a photo-multiplier. The data acquisitions of the interferometer and the graduation signal are synchronous. The light source is a stabilized laser with two frequencies and forms double paths heterodyne interferometers for a mirror on the moving stage and another mirror fixed near objective lens. The displacements of the two mirrors are obtained by optical heterodyne technique. The graduation signal is obtained as an optical intensity change depending on the displacement of the moving stage. The signal is processed as follows. (1) Peek and bottom are determined. (2) two horizontal lines, 25% and 75% are determined. (3) The front edge position L_f is determined so that L_f be equal to the average of $L_{f,25}$ and $L_{f,75}$. (4) The back edge position L_b is determined in the same way. (5) The center position of the graduation L_c is defined as $(L_f + L_b)/ 2$.



On the other hand, scale temperature, air temperature, pressure, humidity are measured. They are used for correction of thermal expansion or air refractive index.

All informations about interferometer, graduations and environments are sent to a personal computer and are processed.

3. Calibration Process

3.1 Acceptance of Calibration

Receive line standard, then confirm the line standard by the serial number, check it by visual testing.

3.2 Preparation

Adjust temperature and humidity of the calibration room.

Set the line standard on the supports at the Bessel points in the interferometer.

Attach three thermometers on the line standard.

Align the line standard by adjusting a support for up/down and far/near directions.

Align the line standard for another support, and repeat these alignments until the alignments for both supports have become good.

Leave the line standard to obtain steady temperature condition for at least two hours for a line standard of shorter than 300mm and for at least four hours for that of equal to or longer than 300 mm.

3.3 Measurement

Turn on the air dryer, turn the lever for air supply and turn on the vacuum pump.

Turn on the orange switch beside the personal computer.

Turn on the micro stage controllers, the halogen lump and the power control unit.

Turn on the photo-multiplier and the personal computer.

Run the program “monitor.exe” and “ssms.exe”.
Set the measurement parameters such as data acquisition interval, moving speed of the stage and the filename.
Start the measurement by pressing the start button.

3.4 Calculation with an Excel Sheet

Thermal expansion compensation is made with the measured temperature at three points by PRT’s.
Refractive index of the air, which is needed for laser wavelength correction, is calculated by using Ciddor's equation recommended by IUGG in 1999.

4. Instruments (LS-** corresponds to an equipment number defined in the quality manual, QMC LS03.)

4.1 Light source

The light source of line standard interferometer is 633 nm He-Ne laser (LS-02). It was calibrated by an iodine stabilized He-Ne laser in our section.

4.2 Interferometer

The main body of line standard interferometer (LS-01) was designed by NRLM and was made by Nikon company. It can measure a line standard up to one meter with a resolution of 0.6 nm. The moving stage is floated by air and is driven by a motor. There are two sets of interferometer, one for a fixed mirror, and the other for a moving mirror.

4.3 Thermometer

NQR thermometer (LS-11) is regarded as our laboratory standard for temperature. It was calibrated at the triple point of pure water by temperature standard section
PRT’s (LS-06) were calibrated in our section using NQR.
PRT’s are used with an ac bridge (LS-03) for line standard temperature and air temperature.
The thermometer system (LS-06 and LS-03) were calibrated in our section so that PRT’s were set in a copper block and covered by low thermal conducting materials.

4.4 Barometer

Quartz frequency barometer (LS-08) is regarded as our laboratory standard for pressure. It was calibrated by pressure standard section. The barometer (LS-05) for line standard interferometer was calibrated in our section using the quartz frequency barometer.

4.5 Humidity

Dew point meter (LS-07) is regarded as our laboratory standard for humidity. It was calibrated by humidity standard section. The humidity sensor (LS-04) for line standard interferometer was calibrated in our section using the dew point meter.

4.6 CO_2 content

A CO_2 content meter (LS-18) was calibrated with standard gas in the humidity standard section. The CO_2 meter measured the CO_2 content in the measurement room. The content was between 350ppm and 550ppm. So, the constant value of 450ppm is used for refractive index correction.

5. Line shape of Nano3 scales

NMIJ did not record the signal shape of 0 mm line. However, NMIJ keeps the line width of Nano3 scales based on the line edges definition mentioned in chpater 2 of Method. The measurement results of average width of 0 mm line are as follows.

Zerodur 3.837 micrometers

Quartz 3.881 micrometers

B) Tabular description of the measurement methods and instruments: NMIJ

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Individual type from Nikon Company Objective lens:x50
Light source	*Halogen lamp*
Wavelength(s)	*White light (Green filter is also used)*
Slit length	*2mm to 6mm*
Slit width	*20 micrometers*
Polarization	*Do not care*
Coherence	*Do not care*
Aperture/magnification	*0.55 at 50 times magnification*
Detection mode	*Reflected and transmitted light*
Detection principle	*Slit fixed, object moved*
Detection velocity	*0.5 mm / sec*
Sampling frequency (image/interferometer)	*e.g. # of images per line ?; synchronous reading of signal and interf. ? Optical intensity of graduation signal and output signals of a set of interferomers are synchronously sampled at a frequency of 300 kHz.*
Edge detection criterion	*Left edge is defined at the average of 25% intensity and 75% intensity. Right edge is also defined by the same way. Line center is defined by the average of the left edge and the right edge.*
Edge detection short term repeatability (1s)	*About 20 nm*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Interferometer light source / wavelength	He-Ne laser at 633 nm	$< 1 * 10^{-8}$ L
Resolution of displac. Interferometer	0.6 nm (wavelength / 1024)	
Interferometer medium	air	
Refractive index:		
=> refractometer:	Not used	
=> Edlen´s formula:	Ciddor’s formula is used instead of Edlen’s	$5 * 10^{-8}$
Air temperature	19.75 – 20.25 degree	0.03 K
Air pressure	Atmosphere (993-1021 hPa)	0.1 hPa
Air humidity	35 – 43 %	2 %
CO_2-content	450 ppm	50 ppm
Guide error	< 3 sec	< 2 sec
Abbe offset	< 0.2 mm	0.1 mm
Alignment error:	$< 2 * 10^{-8}$ L	
Interferometer	$< 1 * 10^{-8}$ L	$< 1 * 10^{-8}$ L
Scale	$< 1 * 10^{-8}$ L	$< 1 * 10^{-8}$ L

OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	*19.7 – 20.2 degree*	*0.01 K*
Number of repeat measure ments in one scale position	*3*	
Number of scale orient.	*2*	
kind of support	*One fixed roller and one rotatable roller at Bessel points*	
clean room class	*100000*	

Measurand 1B: Deviations from nominal length for every 5 mm line, Zerodur: NMIJ

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Laser wavelength λ	N	$1.05\times10^{-9}\ \lambda$	>100	L/λ	$1.05\times10^{-9}\ L$
Air temperature t	N	33.3 mK	30	$0.93\times10^{-6}\ L$	$3.1\times10^{-8}\ L$
Air pressure p	N	0.14 hPa	10	$0.27\times10^{-6}\ L$	$3.8\times10^{-8}\ L$
Air humidity h	N	2.5%	5	$0.01\times10^{-6}\ L$	$2.5\times10^{-8}\ L$
CO_2 content cc	R	58 ppm	5	$0.015\times10^{-8}\ L$	$0.87\times10^{-8}\ L$
Resolution of interferometer r	R	0.18 nm	>100	1	0.18 nm
Abbe's error a	R	4.2 nm	10	1	4.2 nm
Cosine error scale alignment sa	R	150 μm	20	---	$1.5\times10^{-7}\ L$
Scale temperature t_s	N	10.6 mK	30	$0.03\times10^{-9}\ L$	$0.032\times10^{-8}\ L$
Temperature drift of the moving carriage t_c	R	8 mK	10	---	0.62 nm
Thermal expansion coefficient α	N	2×10^{-8}	10	0.285 L	$0.57\times10^{-8}\ L$
Scale graduation g	R	20 nm	20	1	20nm

Formula or expression of uncertainty shall be given in the same way as for MRA C:

$$U_{95\%} = \sqrt{(41\text{nm})^2 + (3.22\times10^{-7}L)^2} \qquad (k = 2.01)$$

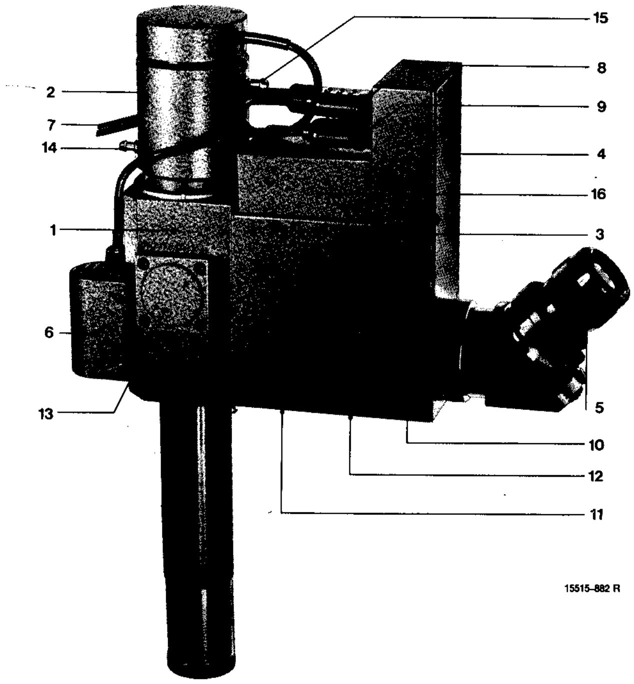
Combined standard uncertainty: $u_c(dl)$ = 50 nm

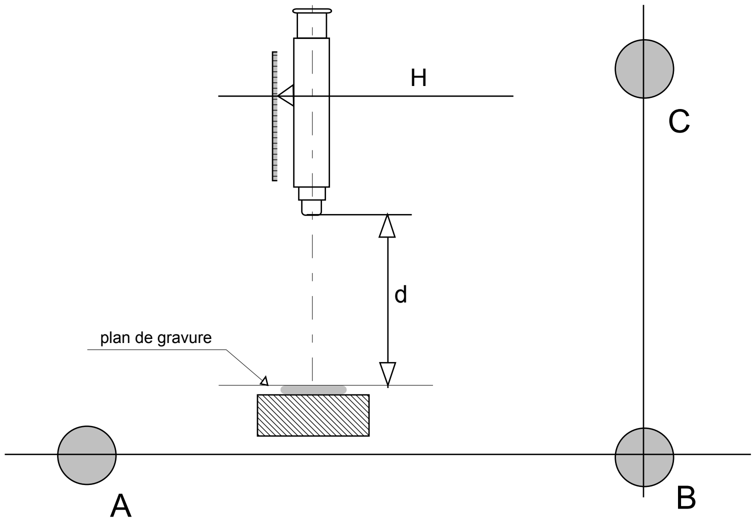
Effective degree of freedom: $\nu_{\text{eff}}(dl)$ = 48

Expanded uncertainty: $U_{95}(dl)$ = 100 nm (k =2.01)

LNE: Measurement report

A) Description of the measurement methods and instruments





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The X value of the intersection of the optical axis of the microscope with the plane of the lines is known through 3 interferometric axis.

Abbe principle could be respected indirectly as the position of the 3 reflectors according to the intersection point are known.

....

B) Tabular description of the measurement methods and instruments: LNE

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Leitz Photoelectric microscope
Light source	*White light*
Wavelength(s)	/
Slit length	*0,1 mm*
Slit width	*2 µm*
Polarization	/
Coherence	/
Aperture/magnification	*10 x*
Detection mode	*Position of a line obseved throught a vibrating slit*
Detection principle	*The position of the line is detected as the signal given by the photomultiplicator passes by a minimum value.*
Detection velocity	5 µm/s
Sampling frequency (image/interferometer)	*The microscope deliver a signal as the center line is detected by the microscope*
Edge detection criterion	/
Edge detection short term repeatability (1s)	*About 40 to 60 nm (depending of line and scale)*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable **standard uncertainty** for measurands
Interferometer light source / wavelength	633 nm	4 fm
Resolution of displac. Interferometer	0,01 µm	
Interferometer medium		
Refractive index:		
=> refractometer:		//
=> Edlen´s formula:	Revised Edlen Formulas	$1\ 10^{-8}$
Air temperature	20 °C	0,03 °C
Air pressure	1013 mbar	9 Pa
Air humidity	50 %	5 %
CO_2-content	300 ppm	60 ppm
Guide error	//	//
Abbe offset	corrected	18 nm
Alignment error:		
Interferometer	0	negligible
Scale	0	$0{,}28\ 10^{-6}$ L

OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	*20 °C*	*0,03 °C*
Number of repeat measurements in one scale position	*10*	
Number of scale orientations	*1*	
kind of support	*Gauge blocks at Airy points*	
clean room class	*no*	

Measurand 1B: Deviations from nominal length for every 5 mm line, Zerodur: LNE

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Repeatability of center line detection SE	/	25 nm	200	1	25 nm
Air wavelength (including t_{air},P_{air},RH $_{air}$, C_{CO2}, λ_0, formulas)	N	0.06 10^{-6} L	12	1	0.06 10^{-6} L
Dl res Interferometer resolution	R.	4.08 nm	200	1	4.08 nm
Errors of interferometer alignement δl_{li}	R.	0.008 10^{-6} L	50	1	0.008 10^{-6} L
Errors of scale alignement δl_{Si}	R	0.0003 10^{-6} L	50	1	0.0003 10^{-6} L
Δt_s scale temperature	N	0.0009 10^{-6} L	12.	1	0.015 10^{-6} L
$\alpha z_{,cr}$ (assumed ± 0.1 10^{-6} K^{-1})	N	0.0017 10^{-6} L	50	1	0.017 10^{-6} L
δl_{Ai} Abbe offset	N	18 nm	12	1	18 nm

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(dl)$ in nm = Qu (31 ; 0,06L) L in mm

Effective degree of freedom: $\nu_{eff}(dl)$ = 103

Expanded uncertainty: $U_{95}(dl)$ in nm = QU (62 ; 0,12L) L in mm

PTB, nmK: Measurement report

A) Description of the measurement methods and instruments

The entire interferometric beam path is in vacuum. The change in distance between the fixed interferometer beam divider and the movable measuring reflector of the main interferometer is made possible through metal membrane bellows. The measuring reflector is mounted on an air cushioned measuring slide. The measured object is arranged on a finely adjustable holder on the measuring slide. Between the measuring reflector and the object holder there is a fixed mechanical coupling. The membrane bellows for the measuring reflector is supported on the bellows slide, which also moves on air bearings. The bellows slide is controlled to remain at a constant distance from the measuring slide, so that the forces of the membrane bellows should not influence the measuring slide. The two slides are moved by separate linear motors using carbon fiber coupling tubes. The slides control is conducted with the aid of two LIP 401 incremental encoders. Different measuring systems for the structure localization can be applied to a universal sensor carrier on a solid bridge above the measuring slide. Incremental scanning heads and a photoelectric slit microscope with a photomultiplier have been used up to now. All parts of the comparator are arranged on a 70-cm thick granite base. The principle of the comparator setup is shown in figure 1.

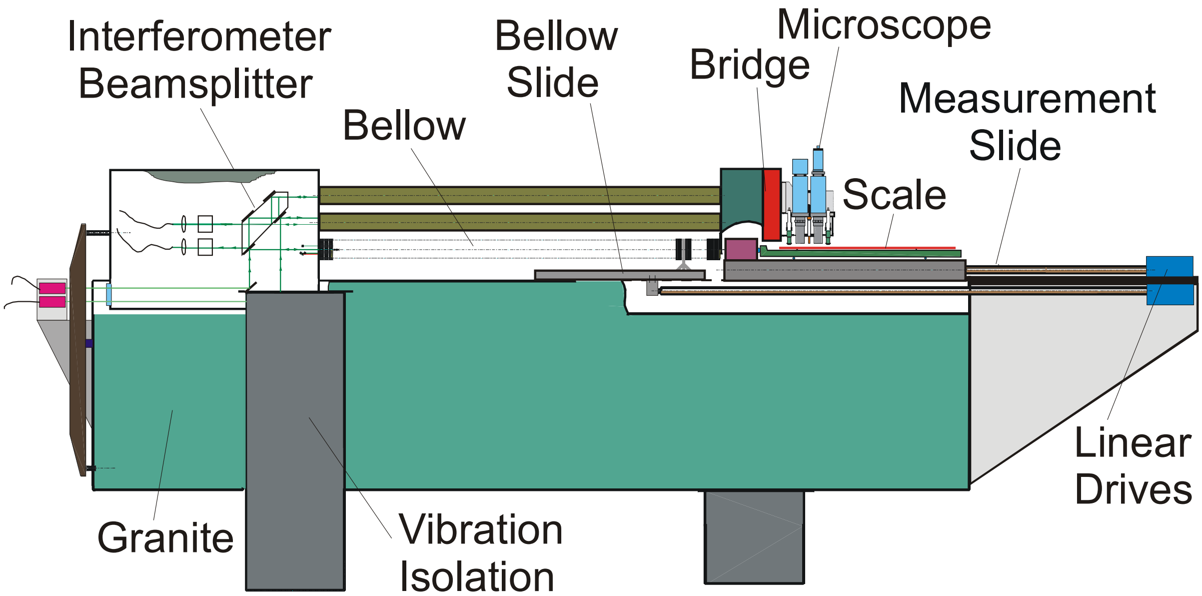

Figure 1 : Principle of the Nanometer Comparator

The measurements for the Nano3 comparison were performed in dynamic mode. In this mode the scale under investigation is moved underneath the photoelectric microscope with a constant speed. A gate signal, which is derived from the intensity signal of the graduation line when it passes the slit of the microscope, electronically turns on and off a clock generator used to trigger the interferometer and the A/D converter of the intensity signal simultaneously. The position of the line is calculated as the average of its left and right edge. Therefore, in the edge regimes, which is defined here as the transition region, where the intensity values are between 35% and 80% of the maximum reflected light intensity of the line, the dependencies of the intensity on the position are approximated by linear functions. From these functions the edge positions are determined as the positions, where the intensity level reached 50% of the maximum intensity of the line.

Both samples were measured two times in each orientation. Each time 36 data sets were taken and averaged. The final result quoted is the average of the different orientations.

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[5] J. Flügge, H.J. Schuster: A high precision temperature measurement system with Pt 100 for precision engineering. in PTB Bericht F-17 : „Temperature Measurements in Dimensional Metrology, 1993.

B) Tabular description of the measurement methods and instruments: PTB nmK

Line detection

Parameters	Parameters used for the measurement
Microscope type:	Slit microscope with scanning object
Light source	*cold light source with green interference filter*
Wavelength(s)	*550 nm*
Slit length	*100 µm*
Slit width	*2 µm*
Polarization	*None*
Coherence	-
Aperture/magnification	*0.55 / 50x (16.1 mm working distance)*
Detection mode	*Photoelectric Microscope*
Detection principle	*Photomultiplier*
Detection velocity	*V = 1 mm/s*
Sampling frequency (image/interferometer)	*Simultanously reading of microscope signal and interferometer at 30 kHz*
Edge detection criterion	*50 % Intensity*
Edge detection short term repeatability (1s)	*5 nm*

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands (1σ)
Interferometer light source / wavelength	*I_2 Stabilised NdYag / 532 nm*	*1E-10L*
Resolution of displac. Interferometer	*0,03 nm*	
Interferometer medium	*Vacuum*	
Refractive index:	*Corrected with Edlen*	*4E-9L*
=> refractometer:		
=> Edlen´s formula:	*Birch, Downs*	
Air temperature		
Air pressure	*$5 * 10^{-2}$ hPa*	
Air humidity		
CO_2-content		
Guide error	*0,5 arcsec*	*4,5*
Abbe offset	*0 ± 2mm*	
Alignment error:		
Interferometer	*6 arcsec*	*4,5E-10L per Axis*
Scale	*2 arcsec*	*5E-11L per Axis*

6 OTHER MEASUREMENT CONDITIONS

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature	0,01K	5,4E-9L (For Quarz)
Number of repeat measurements in one scale position	*36*	
Number of scale orientations	*2*	
kind of support	*Wedge on one side, two rollers under the scale edges on the other side*	
clean room class		

Measurand 1B: Deviations from nominal length, every 5 mm line, Quartz: PTB-nmK

Uncertainty of measurement

name and symbol x_i	distrib.	$u(x_i)$ unit	ν_i	$c_i = \partial dl/\partial x_i$	$u_i(dl)$ /nm
Stage:					
Error due to Abbe offset in z (a_p<2 mm) and pitch, δl_{Ap}	R	1.5 µrad	100	a_p /rad	2.9
Error due to Abbe offset in y (a_y<2 mm) and yaw, δl_{Ay}	R	1.5 µrad	100	a_y·/rad	2.9
Interferometer:*					
Laser vacuum wavelength $\delta\lambda_o$	R	0.05 fm	10	L/λ_0	0.0001 L
Refractive index (at 0.05 hPa), δn	N	$4\text{x}10^{-9}$	4	L	0.004 L
Interf. deadpath error δl_{DP} (mm)	R	200 mm	100	$4\text{x}10^{-9}$	0.8
Diffraction effect of the laser beam, δl_{dif} ($\approx L*(\lambda_0/(\pi*D)^2$; D=12 mm)	R	$2\text{x}10^{-10}$	100	L	0.0002 L
Interf. cosine error δl_{li} (µrad)	R	30 µrad	100	$1.5\text{x}10^{-5}$ L/rad	0.00045 L
Scale:					
Temperature deviation Δt_s	R	10 mK	100	$5.4\text{x}10^{-7}$ L/K	0.0054 L
Thermal expansion coeff. α_z (1/K)	N	$1.5\text{x}10^{-8}$ 1/K	10	L ·0.15 K	0.0022 L
Pressure variation s_{pair} (hPa)	R	1	100	$8.9\text{x}10^{-10}$ L/hPa	0.0009 L
Scale alignment horiz. <u>and</u> vert. δl_{Sh} (µrad)	R	10 µrad	100	$5\text{x}10^{-6}$ L /rad	0.00005 L
Measurement:					
Reproducibility of line det s_E (nm) and measurement series	R	19 nm	19	1	19

* Interferometer nonlinearities could not be measured up to now. Due to the experience with other heterodyne interferometers with spatially seperated beams, they are assumed to be negligible at the given total uncertainty of the comparator.

Formula or expression of uncertainty shall be given in the same way as for MRA C:

Combined standard uncertainty: $u_c(L)$= Q[20; 0.007·L] nm, L in mm, Q[x; y]=$(x^2+y^2)^{½}$

Effective degree of freedom: $\nu_{\text{eff}}(L)$= 22 @ L = 280 mm;

Expanded uncertainty: $U_{95}(L)$= Q[41; 0.015 L] nm, L in mm (k=2.07)

Physikalisch-Technische Bundesanstalt

WGDM-7 Preliminary comparison on nanometrology
According to the rules of CCL key comparisons

NANO 3

LINE SCALE STANDARDS

FINAL REPORT

ANNEX D

Tables of reference values of Nano3 comparison

Braunschweig, August 29, 2003

Tables of reference values of Nano3 comparison

MEASURAND 1A: DEVIATION FROM 280 MM LENGTH

A) Quartz

Nominal total length l (mm)	Deviation from nominal total length dl (nm)	Expanded Uncertainty (95% confidence interval) U_c (nm)
280	- 95.8	15.4

MEASURAND 1A: DEVIATION FROM 280 MM LENGTH

B) Zerodur

Nominal total length l (mm)	Deviation from nominal total length dl (nm)	Expanded Uncertainty (95% confidence interval) U_c (nm)
280	- 88.4	26.6

MEASURAND 1B: 280 MM MAIN GRADUATION, 5 MM STEP

A) Quartz

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)	Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	3.8	140	-56.5	8.8
5	7.6	5.2	145	-52.6	10.4
10	3.0	3.9	150	-65.5	9.2
15	-10.0	5.6	155	-63.2	10.8
20	-12.8	4.2	160	-67.1	9.6
25	-11.6	5.9	165	-65.2	11.2
30	-8.1	4.5	170	-68.2	10.0
35	-3.4	6.3	175	-69.8	11.5
40	-5.1	4.9	180	-80.3	10.3
45	-13.9	6.6	185	-65.6	11.9
50	-19.1	5.2	190	-74.5	10.7
55	-19.6	7.0	195	-74.3	12.3
60	-20.4	5.6	200	-79.0	11.1
65	-22.6	7.4	205	-81.8	12.6
70	-27.0	6.1	210	-79.6	11.4
75	-44.7	7.8	215	-79.2	13.0
80	-29.8	6.5	220	-85.1	11.8
85	-41.4	8.2	225	-96.0	13.3
90	-44.1	6.9	230	-98.2	12.1
95	-47.5	8.6	235	-95.0	13.7
100	-51.7	7.3	240	-100.0	12.5
105	-45.0	8.9	245	-100.7	14.1
110	-42.7	7.7	250	-108.3	12.9
115	-53.6	9.3	255	-106.7	14.4
120	-52.0	8.1	260	-111.9	13.2
125	-48.9	9.7	265	-107.7	14.9
130	-53.2	8.5	270	-112.5	13.6
135	-50.3	10.1	275	-109.7	15.1
			280	-101.2	13.9

MEASURAND 1B: 280 MM MAIN GRADUATION, 5 MM STEP

B) Zerodur

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)	Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	6.3	140	-43.1	14.9
5	-36.2	7.4	145	-20.5	16.5
10	-51.9	6.4	150	-44.4	15.7
15	-53.5	7.6	155	-39.5	17.3
20	-50.7	6.7	160	-49.3	16.5
25	-52.4	7.9	165	-47.5	18.1
30	-47.2	7.1	170	-48.3	17.3
35	-50.8	8.4	175	-40.5	18.9
40	-38.6	7.6	180	-52.5	18.1
45	-46.9	9.0	185	-44.5	19.7
50	-43.0	8.2	190	-49.6	19.0
55	-43.0	9.6	195	-36.5	20.5
60	-40.9	8.8	200	-42.7	19.8
65	-31.9	10.3	205	-39.8	21.3
70	-27.9	9.5	210	-44.0	20.6
75	-48.1	11.1	215	-46.6	22.1
80	-38.4	10.2	220	-44.1	21.4
85	-48.8	11.8	225	-33.6	22.9
90	-46.6	11.0	230	-42.7	22.3
95	-33.0	12.6	235	-59.9	23.7
100	-49.2	11.7	240	-54.3	23.1
105	-41.1	13.3	245	-62.7	24.5
110	-36.3	12.5	250	-76.6	23.9
115	-32.5	14.1	255	-61.7	25.4
120	-38.0	13.3	260	-62.4	24.7
125	-37.7	14.9	265	-55.4	26.3
130	-43.2	14.1	270	-63.1	25.6
135	-24.4	15.7	275	-77.8	27.0
			280	-90.5	26.4

MEASURAND 1C: DEVIATIONS FROM NOMINAL LENGTH FOR 1 MM LINES BUT ONLY WITHIN THE FIRST 20 MM OF THE MAIN GRADUATION

A) Quartz

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	3.4
1	-5.0	3.4
2	-0.8	3.4
3	9.4	3.4
4	5.6	3.5
5	7.0	3.5
6	17.2	3.5
7	10.3	3.5
8	6.4	3.5
9	6.0	3.5
10	4.6	3.5
11	8.4	3.5
12	-0.8	3.5
13	-3.4	3.6
14	-6.6	3.6
15	-8.8	3.6
16	-9.9	3.6
17	-4.5	3.6
18	-10.0	3.7
19	-11.0	3.7
20	-11.1	3.7

MEASURAND 1C: DEVIATIONS FROM NOMINAL LENGTH FOR 1 MM LINES BUT ONLY WITHIN THE FIRST 20 MM OF THE MAIN GRADUATION

B) Zerodur

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	4.0
1	-10.6	4.0
2	-13.8	4.0
3	-22.3	4.0
4	-32.6	4.0
5	-38.8	4.0
6	-46.1	4.0
7	-47.9	4.0
8	-53.7	4.0
9	-52.6	4.0
10	-52.6	4.0
11	-54.4	4.1
12	-54.5	4.1
13	-50.3	4.1
14	-53.0	4.1
15	-59.1	4.1
16	-56.9	4.1
17	-51.4	4.1
18	-52.1	4.1
19	-52.1	4.2
20	-51.4	4.2

MEASURAND 2D: DEVIATIONS FROM NOMINAL LENGTH FOR 47 LINES OF THE GRADUATION WITH 100 µM PITCH (LENGTH OF 4.6 MM, MIDDLE PITCH STRUCTURE GROUP)

A) Quartz

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)	Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	4.0			
0.1	9.3	4.0	2.4	1.2	4.0
0.2	5.3	4.0	2.5	7.5	4.0
0.3	2.3	4.0	2.6	6.4	4.0
0.4	5.6	4.0	2.7	4.2	4.0
0.5	5.2	4.0	2.8	14.3	4.0
0.6	7.5	4.0	2.9	9.1	4.0
0.7	4.3	4.0	3.0	2.2	4.0
0.8	15.0	4.0	3.1	1.4	4.0
0.9	8.3	4.0	3.2	11.4	4.0
1.0	0.5	4.0	3.3	2.5	4.0
1.1	8.3	4.0	3.4	0.4	4.0
1.2	8.9	4.0	3.5	9.9	4.0
1.3	5.4	4.0	3.6	5.0	4.0
1.4	1.5	4.0	3.7	1.0	4.0
1.5	7.5	4.0	3.8	14.9	4.0
1.6	9.4	4.0	3.9	5.4	4.0
1.7	5.7	4.0	4.0	0.0	4.0
1.8	11.2	4.0	4.1	-0.4	4.0
1.9	5.9	4.0	4.2	7.5	4.0
2.0	0.8	4.0	4.3	-0.7	4.0
2.1	-0.8	4.0	4.4	-1.7	4.0
2.2	8.1	4.0	4.5	10.4	4.0
2.3	2.1	4.0	4.6	7.3	4.0

MEASURAND 2D: DEVIATIONS FROM NOMINAL LENGTH FOR 47 LINES OF THE GRADUATION WITH 100 µM PITCH (LENGTH OF 4.6 MM, MIDDLE PITCH STRUCTURE GROUP)

B) Zerodur

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)	Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	3.4			
0.1	5.0	3.5	2.4	-1.7	3.4
0.2	3.1	3.4	2.5	-2.7	3.4
0.3	-1.3	3.4	2.6	-1.1	3.4
0.4	-0.5	3.4	2.7	-4.1	3.4
0.5	-0.8	3.4	2.8	0.2	3.4
0.6	3.0	3.4	2.9	3.1	3.5
0.7	0.6	3.4	3.0	-1.5	3.5
0.8	4.3	3.4	3.1	1.8	3.5
0.9	-0.3	3.4	3.2	-1.1	3.5
1.0	-0.5	3.4	3.3	-2.3	3.5
1.1	4.1	3.4	3.4	0.8	3.5
1.2	0.0	3.4	3.5	-1.0	3.5
1.3	-4.1	3.4	3.6	1.7	3.5
1.4	-1.9	3.4	3.7	-3.4	3.5
1.5	-0.8	3.4	3.8	0.1	3.5
1.6	0.8	3.4	3.9	4.1	3.5
1.7	-3.2	3.4	4.0	-2.9	3.5
1.8	3.5	3.4	4.1	0.3	3.5
1.9	-0.4	3.4	4.2	0.7	3.5
2.0	-2.3	3.4	4.3	-3.9	3.5
2.1	-2.9	3.4	4.4	-0.4	3.5
2.2	2.0	3.4	4.5	4.3	3.5
2.3	-3.2	3.4	4.6	1.1	3.5

MEASURAND 2E: DEVIATIONS FROM NOMINAL LENGTH FOR 47 LINES OF THE GRADUATION WITH 10 µM PITCH (LENGTH OF 0.46 MM, MIDDLE PITCH STRUCTURE GROUP)

A) Quartz

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)	Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	2.8			
0.1	3.9	2.8	2.4	4.3	2.8
0.2	4.8	2.8	2.5	5.5	2.8
0.3	3.3	2.8	2.6	7.5	2.8
0.4	8.3	2.8	2.7	6.0	2.8
0.5	5.2	2.8	2.8	9.2	2.8
0.6	8.6	2.8	2.9	8.2	2.8
0.7	9.1	2.8	3.0	7.3	2.8
0.8	6.2	2.8	3.1	4.7	2.8
0.9	6.7	2.8	3.2	6.0	2.8
1.0	6.8	2.8	3.3	6.3	2.8
1.1	11.9	2.8	3.4	10.9	2.8
1.2	11.2	2.8	3.5	10.2	2.8
1.3	9.0	2.8	3.6	9.6	2.8
1.4	10.3	2.8	3.7	11.9	2.8
1.5	4.2	2.8	3.8	7.4	2.8
1.6	7.8	2.8	3.9	7.3	2.8
1.7	8.9	2.8	4.0	7.7	2.8
1.8	7.2	2.8	4.1	7.2	2.8
1.9	6.7	2.8	4.2	10.9	2.8
2.0	7.3	2.8	4.3	7.7	2.8
2.1	6.4	2.8	4.4	5.2	2.8
2.2	7.0	2.8	4.5	6.9	2.8
2.3	3.1	2.8	4.6	1.8	2.8

MEASURAND 2E: DEVIATIONS FROM NOMINAL LENGTH FOR 47 LINES OF THE GRADUATION WITH 10 µM PITCH (LENGTH OF 0.46 MM. MIDDLE PITCH STRUCTURE GROUP)

B) Zerodur

Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)	Nominal length l (mm)	Deviation dl (nm)	Expanded Uncertainty U_c (nm)
0	0.0	3.3			
0.1	3.8	3.3	2.4	14.4	3.3
0.2	6.2	3.3	2.5	16.6	3.3
0.3	7.7	3.3	2.6	14.9	3.3
0.4	7.2	3.3	2.7	1.7	3.3
0.5	7.4	3.3	2.8	2.7	3.3
0.6	10.8	3.3	2.9	7.7	3.3
0.7	13.4	3.3	3.0	8.8	3.3
0.8	11.6	3.3	3.1	6.9	3.3
0.9	16.5	3.3	3.2	13.0	3.3
1.0	16.9	3.3	3.3	12.7	3.3
1.1	8.0	3.3	3.4	6.7	3.3
1.2	11.7	3.3	3.5	6.7	3.3
1.3	10.7	3.3	3.6	6.1	3.3
1.4	14.9	3.3	3.7	8.6	3.3
1.5	9.2	3.3	3.8	10.2	3.3
1.6	12.6	3.3	3.9	11.4	3.3
1.7	18.9	3.3	4.0	14.8	3.3
1.8	17.8	3.3	4.1	13.9	3.3
1.9	9.8	3.3	4.2	0.1	3.3
2.0	9.9	3.3	4.3	0.5	3.3
2.1	10.8	3.3	4.4	2.9	3.3
2.2	12.9	3.3	4.5	7.6	3.3
2.3	10.4	3.3	4.6	4.7	3.3