NANO5 - 2D Grating - Final report

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Summary

This report is prepared for the **Discussion Group 7 (DG7) for Nanometrology** under the **Consultative Committee for Length's Working Group on Dimensional Metrology (CCL-WGDM)**. It describes the comparison of calibration results of the pitch in the x and y direction and the angle of two two-dimensional gratings. The nominal values of the pitches are 300 nm and 1000 nm and the nominal angle is 90°. The standards were circulated between 12 national metrological institutes. The measurement methods were optical diffraction (OD) and scanning probe microscopy (SPM). The reported uncertainty for the pitch was in the range from 0,0031 nm (OD) to 3,1 nm and for the angle in the range from 0,0012° (OD) to 1,2°. Out of the 112 measurement results for the six measurands, 17 results have either been removed from the calculation of the reference value - due to errors acknowledged by the Lab - or have been omitted as the En values were larger than one. Ten of the results have En values larger than one; six results have En values larger than two. However, the participating Labs have identified errors and submitted a total of 15 corrected measurement values to be considered for inclusion in the calculation of the reference value. In the end only four results remain with an unexplained En value larger than one ranging between 1.4 and 2.1. Acknowledging the errors found by the labs in this comparison, the measurement of pitch and angle are generally consistent and reliable to a very high accuracy.

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Content

1 Introduction

The Discussion Group 7 (DG7) for Nanometrology under the Consultative Committee for Length's Working Group on Dimensional Metrology (CCL-WGDM) decided at its June 1998 meeting at the BIPM to perform a comparison for five different types of artefacts among the interested participants of the meeting including one and two-dimensional (1D and 2D) gratings. It was decided that the comparison of the 1D grating (NANO4) should start before the comparison of the 2D grating (NANO5). The NANO4 comparison was finished in 2000[a].

The NANO5 comparison was announced in the minutes of the 9th meeting of the CCL-WGDM in Beijing, on the 27th and 28th of September 2004.

Formally NANO5 is a pilot study, but the rules for organizing a key comparison have been followed. It will be recommended to the WGDM and CCL that the final report of the NANO5 pilot study (DRAFT B) is accepted as a supplementary comparison and that the results are included in the Key comparison and calibration database (KCDB), Appendix B. All participants have to agree on this.

The pilot laboratory is Danish Fundamental Metrology (DFM).

[a] The Nano4 comparison has later been promoted to be a CCL supplementary comparisons and the results are included in the Appendix B of the MLA.

2 The transfer standards

2.1 General requirements

At the CCL-WGDM DG7 meeting in June 1998 at the BIPM, it was decided to use 2D gratings with pitches between 200 nm and 1000 nm in accordance with the agreed definition of nanometrology. The transfer standards should meet the requirements of different measuring methods such as SEM, STM, AFM or laser diffraction. Nothing was decided about the nominal angle, but most commercial available 2D gratings have pitches with a nominal angle of 90°.

The transfer standards used should be commercially available so that each participating laboratory can, if desired, obtain a transfer standard of the same type for their own.

The choice of grating has been influenced by the choice of grating for the completed comparison NANO4. The combination of the two comparisons should represent the broadest possible range of pitch values, sample material and manufactures. To avoid possible stitching problems known to occur in e-beam lithography[a], holography patterned gratings were preferred.

2.2 Description of the transfer standards

Two gratings named 2D300 and 2D1000 with a 2D pitch of nominally 300 nm and 1000 nm and nominal angle of 90° are chosen.

2D300 : made by Moxtek, nominal 300 nm pitch, nominal orthogonal[b] delivered to DFM 2004-012-09 with the designation “Advanced Surface Microscopy, Inc. Model 2D300 SN: 2336E0204”

2D1000 : made by Ibsen, nominal 1000 nm pitch, nominal orthogonal[c] delivered to DFM year 2002 with the manufactures inscription on the grating SN: A02114.

2D300

The grating with nominally 300 nm pitch is manufactured using a silicon wafer substrate which is coated with a polymer material. The interference pattern is recorded in this material and then coated with about 50 nm of tungsten to provide a reasonable durable coating and an electrical conductive path to ground.

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[a] Influence of nanostandard properties on calibration procedures Th. Dziomba, W. Hässler-Grohn, H. Bosse, H.-U. Danzenbrink, G. Wilkening Proc. 4th International euspen conference. Vol. 2. 491-494 (2003)

[b] Valid link at time of purchase 2004-12-13: www.asmicro.com/calweb.htm. Valid link 2008-02-26: http://www.asmicro.com/Supplies/Calibrator_guide.htm

[c] Valid link at time of purchase 2004-12-13 to pdf flyer: www.nanosensors.com/products_overview.html. This link is still valid 2008-02-26.

A square array of bumps covers the entire chip (approximately 3 mm × 4 mm).

During the comparison the pilot lab realised that the standard (unintentionally) tilted 1.5 degree relative to the plane of the steel disc it was mounted on (the tilt is along the y axis being highest near the black line indicating the x-direction). This is not pointed out explicit in the technical protocol.

For more details see the Technical Protocol Appendix

2D1000

The transfer standard with nominally 1000 nm pitch is manufactured by Ibsen Photonics (Type 2D1000) directly into a SiO_2 layer on a silicon substrate using a holographic principle to pattern a photo resist, followed by development and etching. The surface is covered by chromium and platinum. The 2D pattern, which cover an area of nominal 2.5 mm × 2.5 mm, consist of flat cylinder or squares about 100 nm high on top of a rectangular piece of silicon with the size of 7 mm × 5 mm × 0.5 mm.

For more details see the Technical Protocol

2.3 Orientation and handling

The transfer standards is premounted with silver paint onto steel disks with diameter of 12 to 15 mm and thickness 1 to 2 mm. Marked on the steel disk is the identification and the measurement direction (→ x). **No cleaning of the gratings was allowed** besides blowing away some dust using dry air or other clean gases.

For more details see the Technical Protocol

3 Organisation

Following the rules set up by the BIPM[a] a small group from the provisional list of participating laboratories has drafted a technical protocol. The group is composed of Jørgen Garnaes from the pilot laboratory, Felix Meli from METAS, Switzerland and Leonid Vitushkin from BIPM[b]. The BIPM (through Leonid Vitushkin) and the chairman of the CCL-WGDM and DG7 all act as observers of the comparison and have been informed about the progress of the comparison. Before the circulation of the samples BIPM had to cancel their participation.

3.1 Participants

The participants of the comparison are listed in **Table 1**

DFM – Danish Fundamental Metrology Building 307 Matematiktorvet DK-2800 Lyngby, Denmark	Jørgen Garnaes (Coordinator)	Tel. +45 45 25 5884 Fax +45 45 93 1137 e-mail: jg@dfm.dtu.dk
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CMI - Czech Metrology Institute Okruzni 31 638 00 Brno , Czech Republic	Petr Klapetek	Tel: +420 545 555 304? Fax +420 545 555 283 e-mail: pklapetek@cmi.cz
NIST – National Institute of Standards and Technology 100 Bureau Drive, Stop 8212 Room A117, Metrology Building Gaithersburg, MD 20899-8212, USA	Ronald Dixson, Theodore Vorburger	Tel. +1 301 975 4399 Fax +1 301 869 0822 e-mail: Ronald.dixson@nist.gov

[a] Guidelines for CIPM key comparisons, Appendix F to the MRA

[b] After the time schedule was send out BIPM excused that they were not able to participate.

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Table 1 Participating laboratories and contact persons

3.2 Time schedule

The time schedule is given in **Table 2.** The time schedule gives the approximate calibration time. Note that MIKES – due to technical problems – have measured again on the 2D300 sample in March 2006.

The comparison was carried out in three sequential loops. The period of time available to each laboratory is one month for calibration and transportation to the next participant.

It was the responsibility of the laboratory that the gratings arrive at the next laboratory at the time scheduled.

DFM has, as pilot laboratory, measured the transfer standards first.

Time schedule

Region	Institute		Calibration	Results reported	Information about apparent anomaly	Corrected values	Draft A	Draft B	Adjusted values	Revised Draft B
Pilot Lab	DFM SPM	DK	Jan. 2005	2006-10-23						
EUROMET	METAS OD METAS SPM	CH	Feb. 2005	2005-05-18	2006-08-31				2007-11-08	
EUROMET	PTB OD PTB SPM	DE	March 2005	2005-05-26; 2005-12-08 (addendum)						
EUROMET	NPL OD NPL SPM	UK	April 2005	2005-07-08 2005-07-08	2006-08-31	2006-09-29				
EUROMET	IMGC OD IMGC SPM	IT	May 2005	2006-08-10	2006-08-31	2006-12-11				
EUROMET	CMI OD CMI SPM	CZ	June 2005	2005-06-23 2005-11-16 (addendum)			2007-08-31	2007-10-08		2008-03-07
NORAMET	NIST SPM	USA	July 2005	2006-01-03	2006-08-31	2006-12-15				
Pilot Lab	DFM	DK	NA	NA						
APMP	NMIJ OD NMIJ SPM	JP	Sep. 2005	2005-11-11						
APMP	CMS OD	TW	Oct. 2005	2006-03-14	2006-08-31	2006-09-04			2008-01-11	
APMP	KRISS OD KRISS SPM	KR	Nov. 2005	2006-01-10						
EUROMET	MIKES SPM	FI	Dec. 2005*	2006-04-10						
APMP	NIM OD NIM SPM	CN	Jan. 2006	2006-06-02	2006-08-31					

*Due to technical problems MIKES measured again the 2D300 standard in March 2006

Table 2 Time schedule and date for receiving the results and corrected values.

4 Measurand

The participants have used two methods: one based on optical diffraction (OD) and one based on scanning probe microscopy (SPM). Each laboratory could supply results from more methods and several have done so.

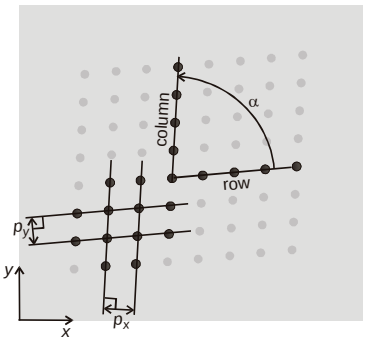

Figure 1 *The grey square indicate the transfer standard with the x and y orientation marked in the corner. The average pitch p_x , and p_y and the average angle α in the anti clockwise direction are shown*

Definitions:

Columns are the protruding structures approximately along the y direction

Rows are the protruding structures approximately along the x direction

The orientations of rows, columns and the anti-clockwise direction, relative to the edges of the rectangular shaped transfer standard and the black line indicating the x-direction on the supporting iron disc are given in **Figure 1.**

Measurand:

The measurands shown also in **Figure 1** are:

1. the average pitch p_x of columns along a line orthogonal to the direction along the columns
2. the average pitch p_y of rows along a line orthogonal to the direction along the rows
3. the average angle α in the anti-clockwise direction between the direction along the rows and the direction along the columns.

All measurands are defined as the average over a surface area of 1 mm × 1 mm. For details in identification of the area see the enclosed Technical Protocol.

The measurands must be stated for the reference temperature of 20°C.

5 Methods of measurements

The methods used by the participants of the comparison are listed in **Table 3**

Country	Institue	Measurement	Instrumentation	Source of Traceability
DK	DFM	SPM	A metrological atomic force microscope (AFM) with a scan area of 70 µm x 70 µm x 6 µm equipped with capacitive distance sensors was used. (Dimension 3100, Veeco, USA)	Traceability was provided by a 2D reference standard (Ibsen, DK), consisting of a nominally 1000 nm pitch square pattern. The standard was calibrated by METAS using optical diffraction.
CH	METAS	OD	Diffractometer built at METAS for Littrow diffraction. The rotary table has air bearings and an incremental encoder for the angular measurements (Heidenhain, RON 905).	The main sources of traceability were the laser wavelength and the diffraction angle. The lasers used were an unstabilised red He-Ne laser (2D1000) and a green mode stabilised He-Ne laser (2D300).
		SPM	A commercial metrology AFM (Dimension 3500 with metrology head from Digital Instruments) equipped with a differential double pass plane mirror interferometer with HeNe laser..	The main sources of traceability is the laser wavelength. The laser used was an unstabilised red He-Ne laser.
DE	PTB	OD	A multiline HeNe laser (Research Electro-Optics Model 30603) which emits at 633 nm, 594 nm and 543 nm, an Ar ion laser (Spectra Physics Model 2045E) with various wavelengths. We used the 496 nm and 476 nm lines, and a Nd-YAG laser the frequency of which has been doubled twice resulting in a UV wavelength of about 266 nm (Crystal GmbH FQSS266-Q). The angle of the turntable is measured using a rotary encoder (Heidenhain RON 255 with Heidenhain IK110).	The traceability to SI units is assured by using laser radiation of well known wavelength.
		SPM	The measurement was carried out with a metrological Large-Range Scanning Probe Microscope (LR-SPM). This instrument consists of the Nano-Measuring-Machine (SIOS Company) with a scanning/positioning range of 25 mm x 25 mm x 5 mm and a scanning force microscope used as zero-detector.	The positions along three co-ordinate axes were measured using three optical interferometers that were illuminated with frequency stabilized lasers. The optical frequencies of the lasers were calibrated to an iodine frequency stabilized laser.
UK	NPL	OD	An optical diffraction method was used to measure average pitch and orthogonality of the gratings. The main components of the diffractometer are a green He-Ne laser and an angle table.	The frequency of the laser has been calibrated traceably at NPL by comparison with an iodine stabilised reference laser. The angle table has been calibrated traceably using a calibrated reference polygon at NPL
		SPM	A scanning Atomic Force Microscope with laser displacement measuring interferometers on along three orthogonal axes and a high precision PZT flexure stage for sample scanning.	Traceability to the metre was obtained by comparison at NPL of the frequency of the lasers used in the AFM against the frequency of an iodine stabilised reference laser.

IT	IMGC	OD	The diffractometer makes use of two He-Ne stabilised lasers (633 and 543 nm) on a goniometric table, “Littrow” (or “auto-collimation”) set-up.	The wavelengths of the two He-Ne stabilised lasers (633 and 543 nm) are traceable to the national length standard. The goniometric table is traceable to the Angle Standard.
		SPM	The Scanning Probe Microscope is based on a sample-moving scanning device using stacked xy and z stages operating with interferometer and capacitance-based controls of displacements.	The laser interferometer is traceable to the national length standard, laser He-Ne (127I2) 4/5.
CZ	CMI	OD	CMI laser diffractometer based on adjusting the back-diffraction of suitable wavelength and measuring the angle by two perpendicular distances: grating – optical bench, transmitted spot – reflected spot. The distances are measured directly by laserinterferometer or by tape calibrated by it.	Iodine stabilized lasers 532nm, 543nm, 633nm or nonstabilized lasers measured simultaneously by wavemeter traceable to iodine stabilized lasers.
		SPM	Atomic force microscope Explorer (ThermoMicroscopes).	Instrument is periodically recalibrated using calibration grating calibrated using iodine stabilized Nd:YAG laser 532nm.
USA	NIST	SPM	The NIST calibrated atomic force microscope (C-AFM) is a custom-designed AFM. A piezoelectrically driven six-axis flexure stage, with a 100 μm range in the x and y directions and heterodyne laser interferometers.	The C-AFM has metrology traceability via the 633 nm wavelength of the I2-stabilized He-Ne laser for all three axes.
JP	NMIJ	OD	The OD consists of a He-Cd laser (l=325 nm, 3 mW, IK3083R-D (0013), Kimmon Electric Co., Ltd.), a rotary table (resolution is 0.002 degree, PST-20 (900440 #09), KOHZU PRECISION Co., Ltd.), XYZ moving tables (moving range is 28 mm, 32 mm and 24 mm respectively, KOHZU PRECISION Co., Ltd.), a two-axes swivel (tilting range is ±17degrees and ±20 degrees, KOHZU PRECISION Co., Ltd.), a laser power monitor (effective diameter of a detector is 10 mm, PM-100 (116), Kimmon Electric Co., Ltd.), a slit whose width is 1.0 mm and optics.	The wavelength is calibrated with a specially constructed wavelength meter and is traceable to a 633-nm iodine stabilized He-Ne laser. The angle was calibrated by using an auto collimator telescope and a polygonal mirror.
		SPM	An atomic force microscope with a differential laser interferometer (DLI-AFM) developed by NMIJ was used for this measurement.	The laser source in the DLI-AFM is directly traceable to the length standard.
TW	CMS	OD	Optical diffractometer, assembled by Center for Measurement Standards (CMS) , based on the Littrow configuration. It consists of a He-Ne laser, a precision rotary table (PRT), a position sensitive de-	To establish the chain of traceability to SI units for the OD, the wavelength of the 633 nm He-Ne laser was traced to an iodine-stabilized He-Ne laser and 543 nm laser was calibrated by a wave meter, and the angle of

			tector (PSD), a polarized beam splitter (PBS), a quarter wave plate (QWP) and reflecting mirrors. Two calibrated He-Ne lasers (543 nm and 633 nm) were used in the OD to measure 300 nm and 1000 nm gratings, respectively.	the precision rotary table (PRT) was traced to a standard polygon. Both of the PRT and polygon were calibrated in the CMS.
KR	KRISS	OD	As light sources, an argon ion laser (λ=487.986 ± 0.004 nm) and a He-Cd laser (λ=325.030 ± 0.005 nm) were used. A converging laser beam was incident on the center of the specimen, and the spot size was approximately 2.0 mm at normal incidence. A diffraction angle (anti-reflecting angle) was chosen as the angle readout of a precision rotary table, when a diffraction spot was located on the center of the quadrant photodiode. The precision rotary table was composed of a rotation stage (RTM350, Newport) and an angle encoder (RPN886, Heidenhain).	The values and uncertainties of wavelength of laser sources were quoted from references2,3. The angle readout of precision rotary table was calibrated by comparing with an indexing table (uncertainty: 0.000 03°), and had the uncertainty of 0.000 09° within the entire measurement range from 0° to 360°.
		SPM	The metrological atomic force microscope (MAFM) is based a commercial AFM head module (Autoprobe M5, ThermoMicroscopes) and modified with a two-axis scanner (P-734.2CL, Physik Instrument) for scanning in the x-y plane, and one-axis transducer (P-753.11C, Physik Instrument) is employed for the tip control in the z-axis direction. They are actuated piezoelectrically with flexure-guided mechanisms, and controlled using built-in capacitive sensors. The maximum measurement range of MAFM is 100 μm × 100 μm × 12 μm (x × y × z). The displacement of specimen and tip is measured using a two-axis laser interferometer (ZMI-1000, Zygo) for x-, y-axis and a built-in capacitive sensor for z-axis. The outputs of interferometer and capacitive sensor are acquired simultaneously with an equally time-spaced trigger signal to construct three-dimensional images1.	The MAFM has meter-traceability directly via two-axis heterodyne interferometer for the x- and y-axis displacement measurement, and the wavelength of laser source was calibrated using an I2 stabilized laser. For the z-axis, the meter-traceability can be established through the calibration process of built-in capacitive sensor using an external interferometer or a calibrated standard artefact.
FI	MIKES	SPM	MIKES used a commercial scanning probe microscope (SPM) PSIA XE-100 for pitch calibration of the samples. The microscope has separate x&y and z scanner for improved movement accuracy and closed loop feedback on each axis. The measurement volume is 12x100x100 μm.	The x and y scales of the SPM were calibrated with NGS-31010 pitch standard. The pitch standard was calibrated by MIKES laser diffraction set-up. The laser used for diffraction calibration was a stabilised green He-Ne (543 nm). Wavelength of laser was calibrated against iodine stabilised reference laser.

CN	NIM	OD	Littrow diffraction, tow mode balance stabilized green and red He-Ne laser, manual angle table (CARLZEISS JENA 473).	The wavelengths of the lasers and the angle of the angle table have been traced to Iodine stabilized He-Ne laser and the angle standard separately.
		SPM	Carl Zeiss Jena AFM, VERITEKT 3. The measuring range of AFM is (x, y, z)=(70,15,15) mm, the resolution is (x, y, z)=(1.25, 0.25,0.12) nm.equipped with an integrated miniaturised three dimensional interferometer system used for the calibration of scanners of AFM. The resolution of the laser interferometers is 0.1nm. The optical arrangement of the laser interferometers has avoided the Abbe error. The calibration is performed parallel to the Abbe directions of the mounted sample. The calibration procedure is carried out before the measurement. The deviations of the scanners have been measured and minimized by correction equation in the calibration software.	Laser traceable to NIM standards, 633nm wavelength of the I2-stabilized He-Ne laser.

Table 3 The methods used by the participating laboratories.

6 Results

The results were received at the dates as stated in **Table 2**. The individual values are stated in **Table 4** to **Table 9** and **Figure 3** to **Figure 8** summarize the measurement results and the corrected values submitted.

The results are clearly marked in the tables whether they are included or excluded from the calculation of the reference value based on the principles in the technical protocol. The six reference values are based on

1. 95 (original) **results**.

2. Two **addendum** certificates to the (original) result - the (original) results were excluded from calculation of the reference value. An addendum is a correction to the original certificate received uninvited, that is, before the pilot has informed any labs about possible anomalous results.

3. Seven **corrected values** (that is, corrected certificates) received after the lab has received the information that their (original) results appeared to be anomalous, but before the lab knew the results of any other lab. The (original) results are excluded from calculation of the reference value.

4. Five **adjusted values**, that is, corrected certificates received after the end of the comparison where all participants were informed about the results reported categorized as "adjusted value". Acceptance of these adjusted values – for inclusion in calculating the reference value - is based on the participating Labs assurance that the adjusted value is due to a correction of very clear and unequivocal errors. The influence of these adjusted values on the reference value and the participants degree of equivalence has been critical evaluated by the Pilot Lab and the possible affected participants have been contacted for comments. The (original) results are excluded from calculation of the reference value.

5. Four (original) results with an En value larger than one are not included in the calculation of the reference values.

To enhance the overview, all values are put on a grey background when they were removed from the calculation of the reference value or when they were omitted because the En value was larger than one. To enhance the readability of the figures *all* corrected values – including the error bars - are drawn in a red colour.

Figure 9 and **Figure 10** give, for the six most accurate measurements, the measured pitch along the y-direction of the two gratings as function of the measured pitch along the x-direction.

A summary of treatment of the anomalous results in calculating the reference value is given in **Table 10** and discussed in further details in the following sections. The participating labs, timing of the (original) results, corrected values and adjusted values are given in **Table 2**.

It should be underpinned that the (original) reported result is the only result of the comparison for the participating Labs. The "corrected values" are only numbers included in the calculating of the reference value.

The correspondence (much more than 100 emails) is kept at DFM for at least five years for further documentation.

6.1 Corrected values

The following labs were asked to check their results for numerical errors on 2006-08-31:

1. The lab with the largest En value (if larger than 1) calculated from all the reported results.

2. Other labs which seems to have En values in the range larger than approximately 2.

Examples of numerical errors which can justify a change in the original reported results for the draft A report are errors in transferring the certificates final results to the table in the technical report or obvious misprints such as misplaced comma.

Numerical errors or typing errors in, for example, the analysis of the measurement or uncertainty (including the malfunction of software algorithms) are suitable for draft B corrections exclusively. Also confusion of input parameters in the analysis is suitable for draft B corrections exclusively. Draft B corrections are throughout this report called "corrected values" to underpin that these values do not take the place of the original reported "result" of the calibration.

Four laboratories have reported errors in eight measurements. Based on the above consideration and the laboratories' descriptions of the errors, none of the original submitted results have been changed. No laboratory has asked to have their results removed.

The above interpretation of the guidelines for dealing with anomalous results was sent to all participants on 2007-08-21, 14:30; no objection has been received.

All participants with anomalous results were asked to consider carefully whether the other measured results from the same method and on the same grating should be omitted for the calculation of the reference value. As earlier noted no laboratory has withdrawn any measurements. Metas and CMS have explicitly confirmed their stated results and uncertainties after the (first) Draft B version of the report.

It was also underpinned for all laboratories to remember that the different measurands should be reported unambiguously. For example, the pitch in

the x direction should not be mistaken with the pitch in the y direction and the angle alpha should not be mistaken with any other angle.

6.2 Adjusted values

The guide or technical protocol does not give directions for the exact procedure to follow if a laboratory realise that a reported result has errors, after the end of the comparison where all participants were informed about the results. However, an erroneous result cannot be included in the calculation of the reference value and therefore a decision has to be taken regarding the further course of action. These cases are summarized in the following subsections.

There are two categories of corrected values:

1. Corrected values are denoted as “corrected values”, when the correction was done *before* any detailed knowledge about the other (original) results was given (Draft A). These cases are discussed in section 6.1 Corrected values.

2. Corrected values are denoted as "adjusted value", when the correction was reported *after* the end of the comparison where all participants had been informed with Draft A. These cases are discussed in this section.

6.2.1 Adjusted value (complementary angle) from METAS

METAS has reported a corrected value (complementary angle) after the end of the comparison (publication of Draft A).METAS discovered a mistake when reporting the angle of the 2D1000 grating. METAS indicated the complementary angle (180°-α) because the results of the two measured diagonals were mixed up.

METAS suggested to include the complementary value of the angle result on the 2D1000 grating for the calculation of the reference value. The angle comparison reference value changed only slightly by -0.0003°. This has no consequence on the inclusion or the exclusion of other values. Additionally, the inclusion reduces the reference value uncertainty by 40% and the average absolute En value of all included participants is reduced by 10%.

Based on the above consideration and the laboratories description of the errors the complementary angle is included in the calculation of the reference value.

6.2.2 Adjusted value (increased uncertainties) from CMS

CMS has realised errors and reported an increased uncertainty value for all there four pitch measurements after the end of the comparison where all participants were informed about the results.

After re-evaluating the uncertainty budget for the 2D grating measurements, CMS has modified part of the uncertainty sources which were underestimated such as the wavelength of the laser and the positioning of PRT rotations. The corrected calibration certificate is shown in the appendices.

For the 2D1000 the reported increased uncertainty changes only slightly the reference value. This has no consequence on the inclusion or the exclusion of other values. Based on the above consideration and the laboratories' descriptions of the errors the values with increased uncertainties are included in the calculation of the reference values.

6.2.2.1 2D300 in the x-direction

For the 2D300 in the x-direction, the increased uncertainty implies that the corrected value from CMS (En = 0.97) will *now* contribute to the reference value following the procedure outlined in the technical protocol. This has *no* consequence on the inclusion or the exclusion of the (original) results. In particular, the En values for CMS (2.60) and NIST (-2.27) for their (original) results still remain larger than 1. Based on the above consideration and the laboratories' descriptions of the errors, the value with increased uncertainty is included in the calculation of the reference value.

6.2.2.2 2D300 in the y-direction

Following the procedure of the technical protocol for the 2D300 in the y-direction, including the result from CMS with the increased uncertainty implies that NPL has the highest En value of 1.17, METAS 1.12 and CMS 0.82. After the exclusion of the NPL value, CMS becomes incompatible with En=1.21 (denominator negative). The En values are now 1.18 for NPL and 0.8 for METAS. Excluding CMS as well gives CMS an En value of 1.22 (denominator positive), for NPL En = 1.48 and for METAS En=0.08. The consistency of the results is confirmed by the Birge ration of 0.52, see section 7.3 Consistency of results.

One could argue that it is not completely satisfactory to include CMS's adjusted value in the calculation of the reference value as results were know by all participants and that the adjusted value should be excluded completely - and as a consequence also all the other adjusted values from CMS and also METAS (complementary angle). However, this will not change anything for 2D300 in the y-direction. Following the procedure of the technical protocol (CMS excluded) will give NPL an En value of 2.03 (minus in denominator) as the highest En value and METAS will obtain an En value of 0.83 (with CMS having an En = 1.31). Excluding NPL at this point will give the same result as above.

Based on the above consideration, that is

1. the (original) reported value with a too little uncertainty should *never* contribute to the reference value,

2. the laboratories description of the errors and

3. the influence on the reference value and the equivalence.

The value with increased uncertainty from CMS is – in principle – included in the calculation of the reference value but excluded because the En value is higher than one. For the y-direction of 2D300 it will not change the final result whether the adjusted value is initially excluded or initially included and then excluded due to an En value larger than. In both cases the results from NPL, the (original) result and adjusted value from CMS and the (original) result from NIST will be excluded as their En values are larger than one.

6.3 Surface quality

Five laboratories made a thorough surface quality report, see appendix C.

The surface quality was verifiably deteriorating during the comparison. This might not influence OD measurements, while it certainly influences SPM measurements.

Inspecting carefully the supplied images of KRISS, MIKES[a] (see **Figure 2**) and NIM it is found that cracks are only visible on the MIKES images. On the MIKES and NIM images the big "V" shaped scratch appears. On the KRISS and NIM images no cracks are found, however the image quality is at the limit for such a decision. In conclusion KRISS has not reported any problems regarding neither OD or SPM measurements or damage of the surface; the first to report damage is NIM which measured after KRISS.

In general the figures show no evidence that the reference values should have drifted significant during the comparison.

The conclusion of e.g. Nano4 was that no significant drift was observed for standards similar to the standard used in this comparison[b].

At the end of the comparison, DFM examined both the samples by optical microscopy and attempted to do an AFM measurement in the centre areas to verify the surface quality. It was found that the quality at the centre area was no longer suitable for the highest accuracy of AFM measurements.

[a] Note that the images from MIKAS is recorded before the *second* measurement at MIKAS march 2006 as the very last measurement of the comparison

[b] The two 1D-gratings used in Nano4 were made by the same manufacture and using the same technology as for the 2D300 in this comparison. The nominal period for the 2D300 is equal to nominal period of one of the grating used in Nano4. In fact is was concluded in the Nano4 report that there was no significant difference between two different standards from the same batch.

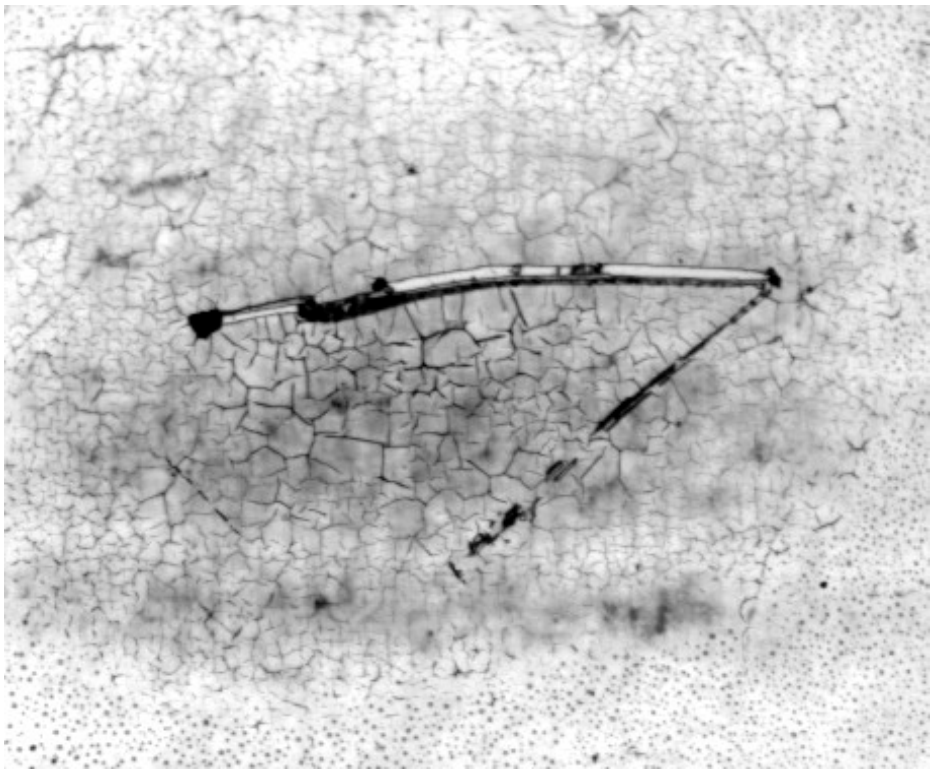

Figure 2 Optical microscopy images of the 2D300 standard before MIKAS measured the sample the second time march 2006 as the *last* measurement of the comparison. Some cracks are seen in the centre and a "V" shaped scratch. MIKAS measured at an alternative spot[a].

[a] In Nano4 it was concluded – for similar samples - that even tow different sets of standards were identical, that is, there was no significant difference in the period.

2D1000 x-direction*		
p_{ref} =	1000,1204	nm
$u_c(p_{ref})$ =	0,0028	nm
$n_{ref}(p_{ref})$ =	192	
$U_{95}(p_{ref})$ =	0,0056	nm

*The reference value is calculated based on 18 (original) results and 2 corrected or adjusted values; 2 (original) results have been omited from the calculation of the reference value.

	2D1000 x-direction									
	Results					Corrected or adjusted values				
	p_x [nm]	u_c [nm]	ν_{eff}	d [nm]	En*	p_x [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**
DFM SPM	1000,130	0,081	99999	0,0096	0,06					
METAS OD	1000,1217	0,0034	107	0,0013	0,36					
METAS SPM	1000,217	0,089	11	0,0966	0,49					
PTB OD	1000,120	0,009	50	-0,0004	-0,02					
PTB SPM	1000,1213	0,0076	40	0,0009	0,07					
NPL OD	1000,070	0,030	27	-0,0504	-0,82					
NPL SPM [a]	1000,01	0,12	26	-0,1104	-0,45					
Corrected NPL SPM[b]						1000,01	0,5	9	-0,1104	-0,10
INRIM OD	1000,34	0,28	42	0,2196	0,39					
INRIM SPM	1001,1	1,2	38	0,9796	0,40					
CMI OD	1000,11	0,034	99999	-0,0104	-0,16					
CMI SPM	1002,9	3,1	200	2,7796	0,45					
NIST SPM	999,78	0,57	108,5	-0,3404	-0,30					
NMIJ OD	1000,01	0,35	10,4	-0,1104	-0,14					
NMIJ SPM	999,87	0,39	19,2	-0,2504	-0,31					
CMS OD[a]	1000,144	0,034	27	0,0236	0,34					
Adjusted CMS OD[c]						1000,144	0,073	157	0,0236	0,16
KRISS OD	1000,108	0,013	107	-0,0124	-0,49					
KRISS SPM	1000,03	0,17	159	-0,0904	-0,27					
MIKES SPM	1000,4	1,7	32	0,2796	0,08					
NIM OD	1000,08	0,08	112	-0,0404	-0,25					
NIM SPM	1000,43	0,44	25	0,3096	0,34					

[a] The (original) result is not included in the calculation of the reference value as the Lab has acknowledged errors and submitted corrections.

[b] *Corrected value* is *included* in the calculation of the reference value

(c) The Lab has reported a corrected value (increased uncertainty) catogrized as "adjusted value"after the end of the comparison where all participants were informed about the result. The adjusted value is included in the calculation of the reference value; the original result is ommitted.

*En value is calculated with a minus sign in the denominator for values *included* in the reference value and a plus sign in the denominator if the value is *not* included in the calculation of the reference value

Table 4 Results for the pitch in the x-direction of 2D1000.

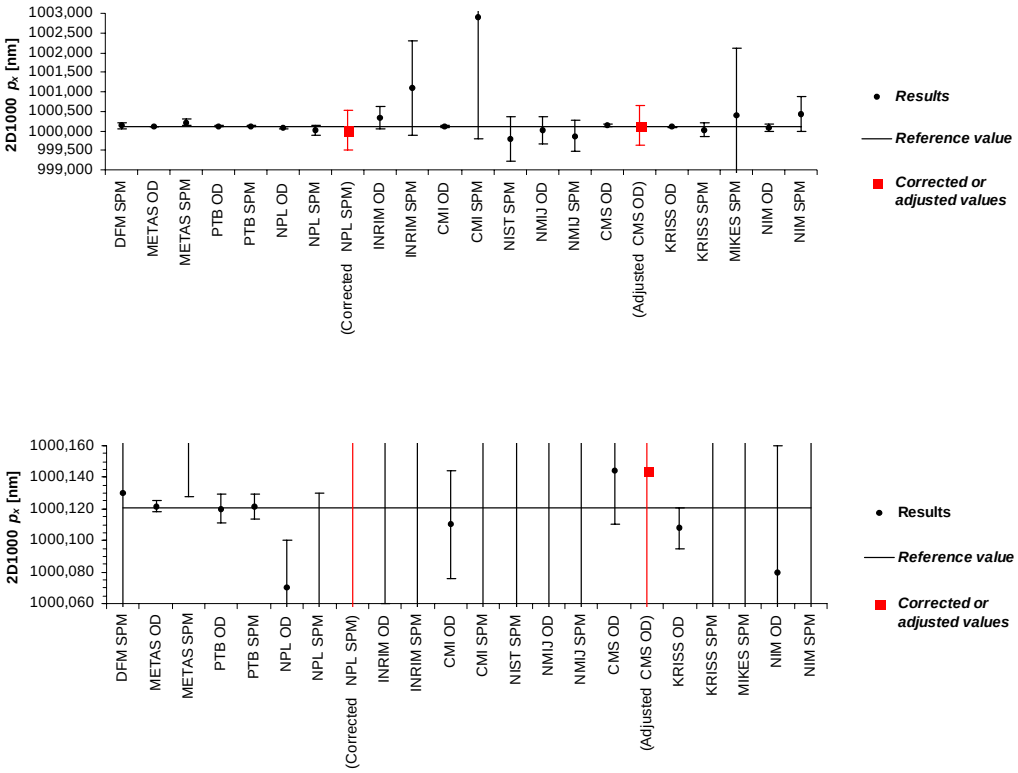

Figure 3 Results for the pitch in the x-direction of 2D1000. The error bars are the reported combined standard uncertainties u_c .

2D1000 y-direction*		
p_{ref} =	999,9458	nm
$u_c(p_{ref})$ =	0,0028	nm
$\nu_{ref}(p_{ref})$ =	233	
$U_{95}(p_{ref})$ =	0,0055	nm

*The reference value is calculated based on 17 (original) results and 3 addendum, corrected or adjusted values; 3 (original) results have been omited from the calculation of the reference value.

	2D1000 y-direction									
	Results					Addendum, corrected or adjusted values				
	p_y [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**	p_y [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**
DFM SPM	999,934	0,095	99999	-0,0118	-0,06					
METAS OD	999,9462	0,0033	140	0,0004	0,11					
METAS SPM	1000,04	0,11	10	0,0942	0,38					
PTB OD	999,950	0,010	50	0,0042	0,22					
PTB SPM	999,9461	0,0073	39	0,0003	0,02					
NPL OD	999,98	0,026	99999	0,0342	0,67					
NPL SPM [(a) (e)]	999,61	0,14	20	-0,3358	-1,15					
Corrected NPL SPM[(c)]						999,61	0,51	10	-0,3358	-0,30
INRIM OD	1000,20	0,22	42	0,2542	0,57					
INRIM SPM	1000,9	1,2	38	0,9542	0,39					
CMI OD [(a) (b)]	999,950	0,042	99999	0,0042	0,05					
Addendum CMI OD [(b)]						999,940	0,042	99999	-0,0058	-0,07
CMI SPM	1005,1	3,5	257	5,1542	0,75					
NIST SPM	999,53	0,72	30,7	-0,4158	-0,28					
NMIJ OD	999,91	0,35	10,4	-0,0358	-0,05					
NMIJ SPM	999,97	0,28	22,3	0,0242	0,04					
CMS OD[(a)]	999,961	0,032	34	0,0152	0,23					
Adjusted CMS OD[(d)]						999,961	0,072	165	0,0152	0,11
KRISS OD	999,923	0,013	104	-0,0228	-0,91					
KRISS SPM	999,96	0,16	214	0,0142	0,04					
MIKES SPM	1000,9	1,7	32	0,9542	0,28					
NIM OD	999,90	0,07	90	-0,0458	-0,33					
NIM SPM	1000,33	0,48	35	0,3842	0,39					

[(a)] The (original) result is not included in the calculation of the reference value as the Lab has acknowledge errors and submitted corrections.

[(b)] Addendum to above certificate before the pilot lab has drawn attention to possible anomalous results; *result of addendum* is *included* in the calculation of the reference value

[(c)] *Corrected value* is *included* in the calculation of the reference value

(d) The Lab has reported a corrected value (increased uncertainty) catogrized as "adjusted value" after the end of the comparison where all participants were informed about the results. The adjusted value is *included* in the calculation of the reference value; the (original) result is ommitted.

[(e)] Lab has been informed by the pilot lab that the result "appears to be anomalous"

*En value is calculated with a minus sign in the denominator for values *included* in the reference value and a plus sign in the denominator if the value is *not* included in the calculation of the reference value

Table 5 Results for the pitch in the y-direction of 2D1000.

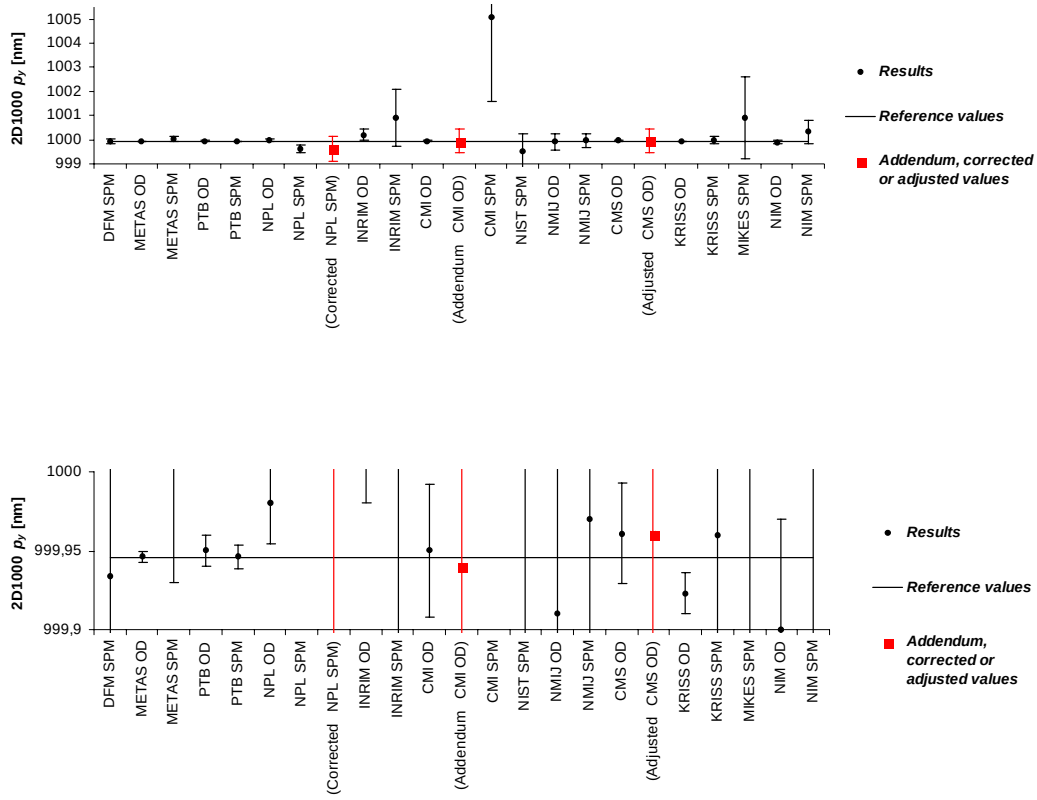

Figure 4 Results for the pitch in the y-direction of 2D1000. The error bars are the reported combined standard uncertainties u_c.

2D1000 Angle*		
α_{ref} =	90,01050	nm
$u_c(\alpha_{ref})$ =	0,00047	nm
$\nu_{ref}(\alpha_{ref})$ =	284	
$U_{95}(\alpha_{ref})$ =	0,00093	nm

*The reference value is calculated based on 17 (original) results and 1 adjusted value; 3 (original) results have been omited from the calculation of the reference value.

	2D1000 Angle									
	Results					Adjusted values				
	a [°]	u_c [°]	ν_{eff}	d [°]	En*	a [°]	u_c [°]	ν_{eff}	d [°]	En*
DFM SPM	90,030	0,083	99999	0,0195	0,12					
METAS OD[(a)(d)]	89,9897	0,0006	140	-0,0208	-13,79					
Adjusetd METAS OD[(e)]						90,0103	0,0006	140	-0,0002	-0,28
METAS SPM	90,006	0,014	23	-0,0045	-0,16					
PTB OD	90,0121	0,0012	50	0,0016	0,72					
PTB SPM	90,0099	0,0016	40	-0,0006	-0,19					
NPL OD	90,0092	0,0022	161	-0,0013	-0,31					
NPL SPM	89,98	0,10	202	-0,0305	-0,15					
INRIM OD	90,024	0,010	12	0,0135	0,62					
INRIM SPM	89,91	0,25	55	-0,1005	-0,20					
CMI OD	90,00	0,08	99999	-0,0105	-0,07					
CMI SPM[(b)]	90,63	0,22	25	0,6195	1,37					
NIST SPM	90,006	0,019	9	-0,0045	-0,10					
NMIJ OD	89,990	0,052	19,6	-0,0205	-0,19					
NMIJ SPM	90,0192	0,0478	35,6	0,0087	0,09					
CMS OD	90,008	0,004	6	-0,0025	-0,26					
KRISS OD	90,0106	0,0018	200	0,0001	0,03					
KRISS SPM	90,008	0,023	420	-0,0025	-0,06					
MIKES SPM	90,06	0,37	8	0,0495	0,06					
NIM OD	89,997	0,31	36	-0,0135	-0,02					
NIM SPM[(c)(d)]	89,9812	0,0065	15	-0,0293	-2,11					

[(a)] The (original) result is not included in the calculation of the reference value as the Lab has acknowledged errors and submitted corrections.

[(b)] *Not* included in the calculation of the reference value (originally En = 1.37).

[(c)] The (original) result is not included in the calculation of the reference value (originally En = -2,12).

[(d)] Lab has been informed by the pilot lab that the result "appears to be anomalous".

[(e)] The Lab has reported a corrected value (complementary angle) catogrized as "adjusted value" after the end of the comparison where all participants were informed about the results. The adjusted value is *included* in the calculation of the reference value.

*En value is calculated with a minus sign in the denominator for values *included* in the reference value and a plus sign in the denominator if the value is *not* included in the calculation of the reference value.

Table 6 Results for the angle measurement of 2D1000.

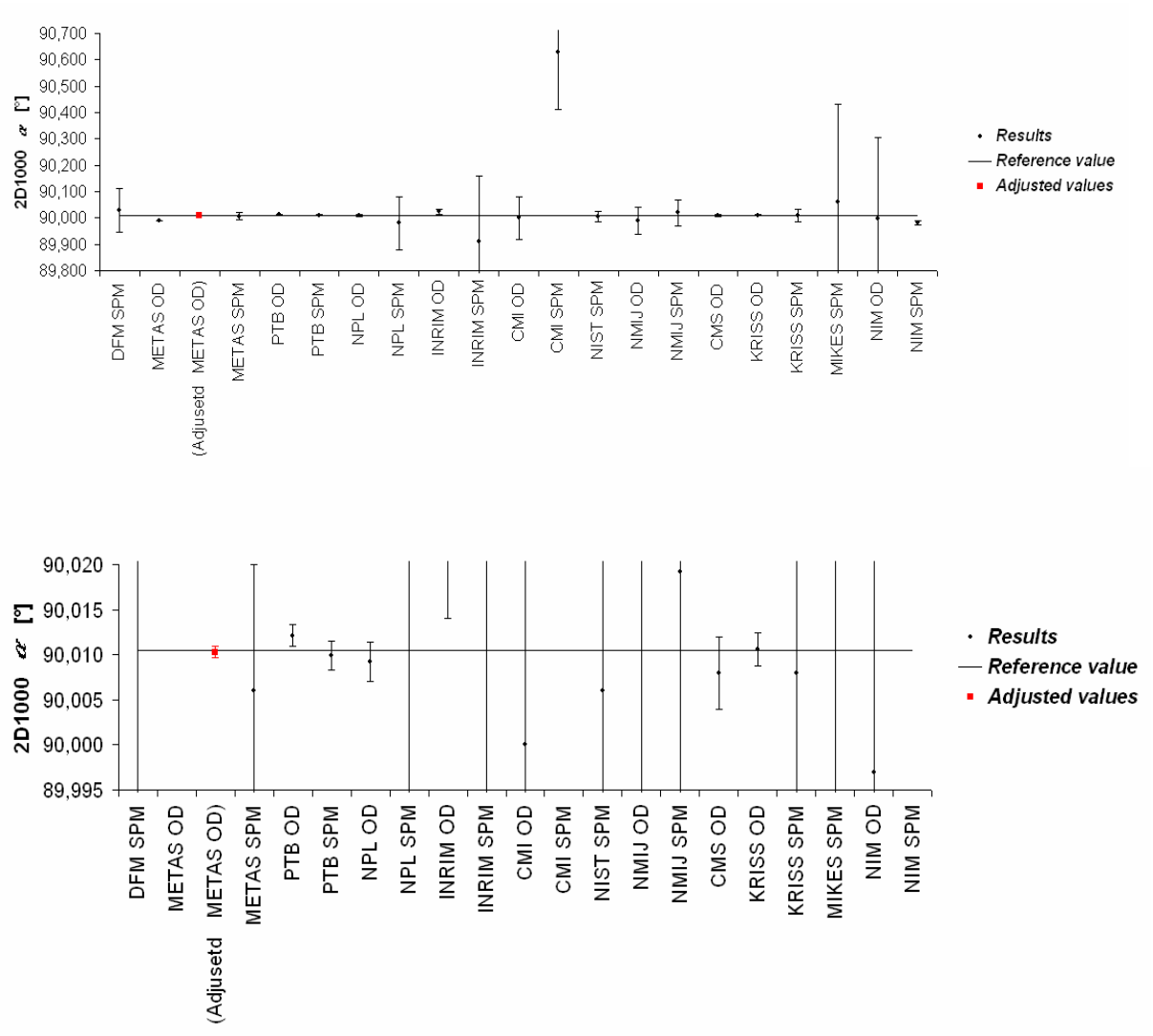

Figure 5 Results for the angle measurement of 2D1000. The error bars are the reported combined standard uncertainties u_c .

2D300 x-direction*		
x_{ref} =	292,0620	nm
$u_c(x_{ref})$ =	0,0017	nm
$\nu_{ref}(x_{ref})$ =	358	
$U_{95}(x_{ref})$ =	0,0034	nm

*The reference value is calculated based on 15 (original) results and 3 corrected or adjusted values; 3 (original) results have been omited from the calculation of the reference value.

	2D300 x-direction									
	Results					Corrected or adjusted value				
	p_x [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**	p_x [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**
DFM SPM	292,075	0,072	99999	0,0130	0,09					
METAS OD	292,0578	0,0031	119	-0,0042	-0,83					
METAS SPM	292,077	0,074	12	0,0150	0,09					
PTB OD	292,046	0,012	50	-0,0160	-0,67					
PTB SPM	292,0544	0,0054	10	-0,0076	-0,66					
NPL OD	292,066	0,0043	505	0,0040	0,51					
NPL SPM [a]	292,37	0,15	25	0,3080	0,997					
Corrected NPL SPM[b]						292,37	0,40	10	0,3080	0,35
INRIM OD	292,069	0,09	20	0,0070	0,04					
INRIM SPM	292	1	46	-0,0620	-0,03					
CMI OD	292,08	0,041	99999	0,0180	0,22					
CMI SPM	293,6	1,4	55	1,5380	0,55					
NIST SPM [a] [c]	290,89	0,26	102,7	-1,1720	-2,27					
Corrected NIST SPM[b]						292,11	0,20	127	0,0480	0,12
NMIJ OD	292,055	0,085	10,5	-0,0070	-0,04					
NMIJ SPM	292,47	0,49	21,2	0,4080	0,40					
CMS OD [a] [c]	292,076	0,002	22	0,0140	2,60					
Corrected CMS OD [d]						292,067	0,002	22	0,0050	0,92
Adjusted CMS OD [e]						292,067	0,0031	129	0,0050	0,97
KRISS OD	292,0644	0,0060	82	0,0024	0,21					
KRISS SPM	292,023	0,094	26	-0,0390	-0,20					
MIKES SPM	291,5	1,7	32	-0,5620	-0,16					

[a] The (original) result is not included in the calculation of the reference value as the Lab has acknowledged errors and submitted corrections.

[b] *Corrected value* is *included* in the calculation of the reference value

[c] Lab has been informed by the pilot lab that the (original) result "appears to be anomalous"

[d] The *corrected value* is *not* included in the calculation of the reference value as the Lab has acknowledged further errors and submitted further corrections catogrized as "adjusted value".

[e] The Lab has reported a corrected value (increased uncertainty) catogrized as "adjusted value" after the end of the comparison where all participants were informed about the results. The adjusted value is included in the calculation of the reference value.

*En value is calculated with a minus sign in the denominator for values *included* in the reference value and a plus sign in the denominator if the value is *not* included in the calculation of the reference value

Table 7 Results for the pitch in the x-direction of 2D300.

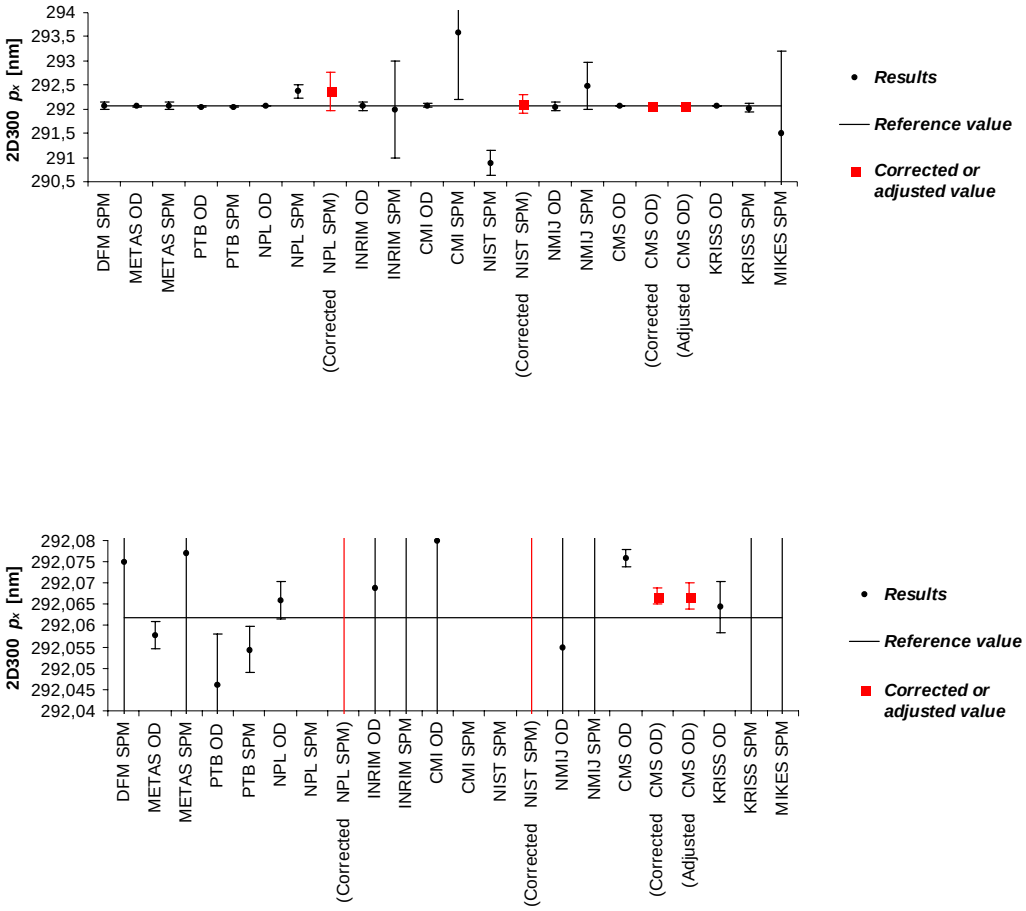

Figure 6 Results for the pitch in the x-direction of 2D300. The error bars are the reported combined standard uncertainties u_c .

2D300 y-direction*		
x_{ref} =	292,0733	nm
$u_c(x_{ref})$ =	0,0024	nm
$\nu_{ref}(x_{ref})$ =	133	
$U_{95}(x_{ref})$ =	0,0048	nm

*The reference value is calculated based on 14 (original) results and 2 corrected or adjusted values; 4 (original) results have been omited from the calculation of the reference value.

	2D300 y-direction									
	Results					Corrected or adjusted value				
	p_y [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**	p_y [nm]	u_c [nm]	ν_{eff}	d [nm]	*En**
DFM SPM	292,102	0,070	99999	0,0287	0,21					
METAS OD [a] [d]	292,073	0,0031	119	-0,0003	-0,08					
METAS SPM	292,081	0,042	16	0,0077	0,09					
PTB OD	292,068	0,014	50	-0,0053	-0,19					
PTB SPM	292,0717	0,0054	10	-0,0016	-0,15					
NPL OD[f]	292,088	0,0044	186	0,0147	1,48					
NPL SPM[b]	292,10	0,15	32	0,0267	0,09					
Corrected NPL SPM[c]						292,10	0,51	32	0,0267	0,03
INRIM OD	292,055	0,090	15	-0,0183	-0,10					
INRIM SPM	291,9	1,0	46	-0,1733	-0,09					
CMI OD	292,070	0,041	99999	-0,0033	-0,04					
CMI SPM	295,8	2,3	177	3,7267	0,82					
NIST SPM [b]	290,59	0,32	112,7	-1,4833	-2,34					
Corrected NIST SPM[c]						292,21	0,20	130,80	0,1367	0,35
NMIJ OD	292,061	0,085	10,5	-0,0123	-0,07					
NMIJ SPM	292,31	0,41	20	0,2367	0,28					
CMS OD[b]	292,083	0,002	18	0,0097	1,52					
Adjusted CMS OD [e]						292,083	0,0032	112	0,0097	1,22
KRISS OD	292,0776	0,0064	84	0,0043	0,36					
KRISS SPM	292,08	0,10	22	0,0067	0,03					
MIKES SPM	293,5	1,7	32	1,4267	0,41					

[a] Based on *all* original and corrected values En = 1,12; excluding then only NPL OD (with the heighest En value of 1,17) gives En = 0.8 for METAS. Excluding now CMS, which have an En value larger than one gives the stated values with En = -0.08 for METAS. The (original) result from METAS is *included* in calculating the reference value. Based on the (original) result only (that is *including* for example the later withdrawn results from CMS OD) gives an En vakue of -1,31 explaining that the Lab was originally informed that the (original) result "appear to be anomalous".

[b] The (original) result is not included in the calculation of the reference value as the Lab has acknowledged errors and has submitted corrections.

[c] *Corrected value* is *included* in calculation of reference value.

[d] Lab has been informed by the pilot lab that the (original) result "appears to be anomalous".

[e] The Lab has reported a corrected value (increased uncertainty) catogrized as "adjusted value" after the end of the comparison where all participants were informed about the results. Based on all original and corrected values CMS has En = 0,82, excluding then NPL (with the heighest En value of 1,17) gives the heighest En value of 1,22 for CMS. *Neither* the (original) result or the adjusted value from CMS is included in calculating the reference value.

[f] Based on all original and corrected values the calculated En value of 1,17 (denominator negative) was the heighest, and the result ommitted in further analysis. The result is not included in the calculation of the reference value. Based on the (original) result only En < 1 (denominator negative) therefore the Lab was not informed before draft A that the (original) result "appears to be anomalous".

*En value is calculated with a minus sign in the denominator for values *included* in the reference value and a plus sign in the denominator if the value is *not* included in the calculation of the reference value

Table 8 Results for the pitch in the y-direction of 2D300.

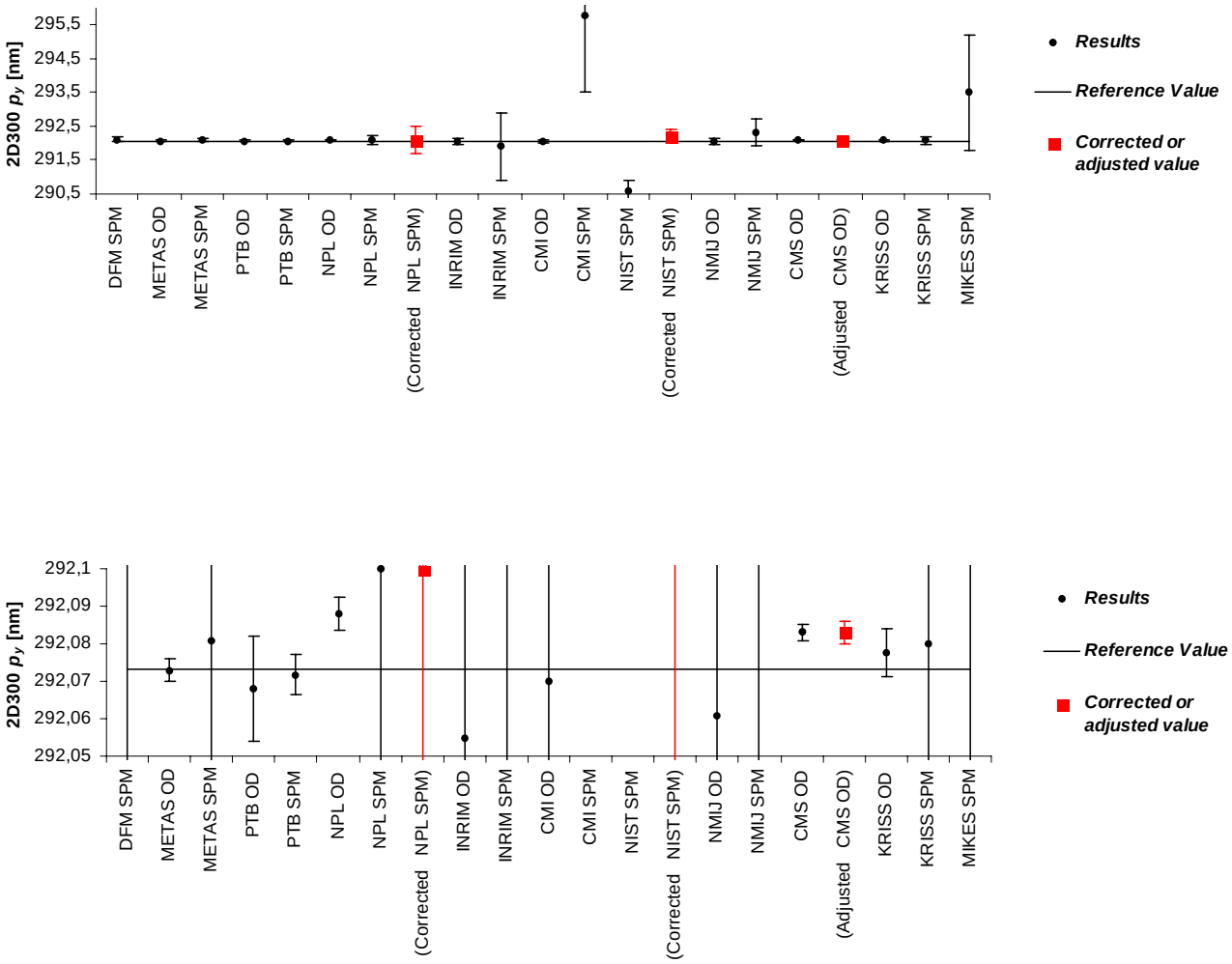

Figure 7 Results for the pitch in the y-direction of 2D300. The error bars are the reported combined standard uncertainties u_c .

2D300 Angle*		
α_{ref} =	90,5456	nm
$u_c(\alpha_{ref})$ =	0,0016	nm
$\nu_{ref}(\alpha_{ref})$ =	134	
$U_{95}(a_{ref})$ =	0,0031	nm

*The reference value is calculated based on 14 (original) results and 2 caddendum or corrected value; 2 (original) results have been omited from the calculation of the reference value

2D300 Angle

	Results					Addendum and corrected values				
	a [°]*	u_c [°]*	ν_{eff}	d [°]	*En**	a [°]*	u_c [°]*	ν_{eff}	d [°]	*En**
DFM SPM	90,521	0,086	99999	-0,0246	-0,15					
METAS OD	na	na								
METAS SPM	90,523	0,029	21	-0,0226	-0,38					
PTB OD [a]	90,554	0,0055	50	0,0084	0,73					
Addendum PTB OD [b]						90,548	0,0055	50	0,0024	0,22
PTB SPM	90,5352	0,0172	8	-0,0104	-0,26					
NPL OD	90,5457	0,0023	44	0,0001	0,02					
NPL SPM	91,05	0,54	5,5	0,5044	0,36					
INRIM OD [a] [d]	89,454	0,01	10	-1,0916	-48,52					
Corrected INRIM OD[c]						90,546	0,01	10	0,0004	0,02
INRIM SPM	90,53	0,33	55	-0,0156	-0,02					
CMI OD	na	na								
CMI SPM	90,35	0,21	22	-0,1956	-0,45					
NIST SPM	90,491	0,078	5,3	-0,0546	-0,27					
NMIJ OD	90,556	0,03	31,5	0,0104	0,17					
NMIJ SPM	90,5107	0,233	17,2	-0,0349	-0,07					
CMS OD	90,546	0,005	6	0,0004	0,03					
KRISS OD	90,5453	0,0028	141	-0,0003	-0,07					
KRISS SPM	90,543	0,045	49	-0,0026	-0,03					
MIKES SPM	90,1	1,2	8	-0,4456	-0,16					

[a] The (original) result is not included in the calculation of the reference value as the Lab has acknowledge errors and submitted corrections

[b] Addendum to above certificate before any response from pilot lab was recieved regarding possible anomalous results; *result of addendum* is *included* in the calculation of the reference value

[c] The corrected value is included in the calculation of the reference value.

[d] Lab has been informed by the pilot lab that the (original) result "appear to be anomalous"

*En value is calculated with a minus sign in the denominator for values *included* in the reference value and a plus sign in the denominator if the value is *not* included in the calculation of the reference value

Table 9 Results for the angle measurement of 2D300.

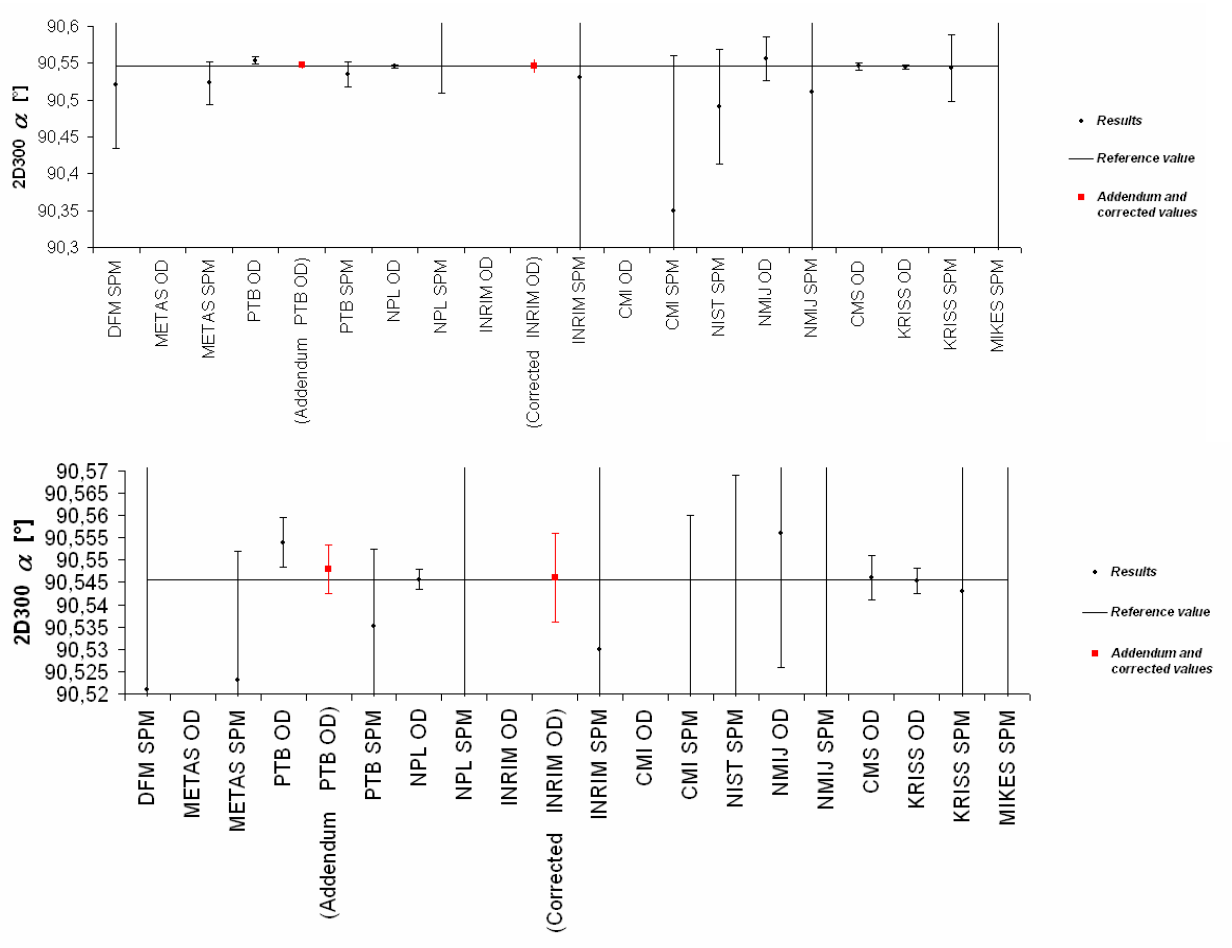

Figure 8 Results for the angle measurement of 2D300. The error bars are the reported combined standard uncertainties u_c .

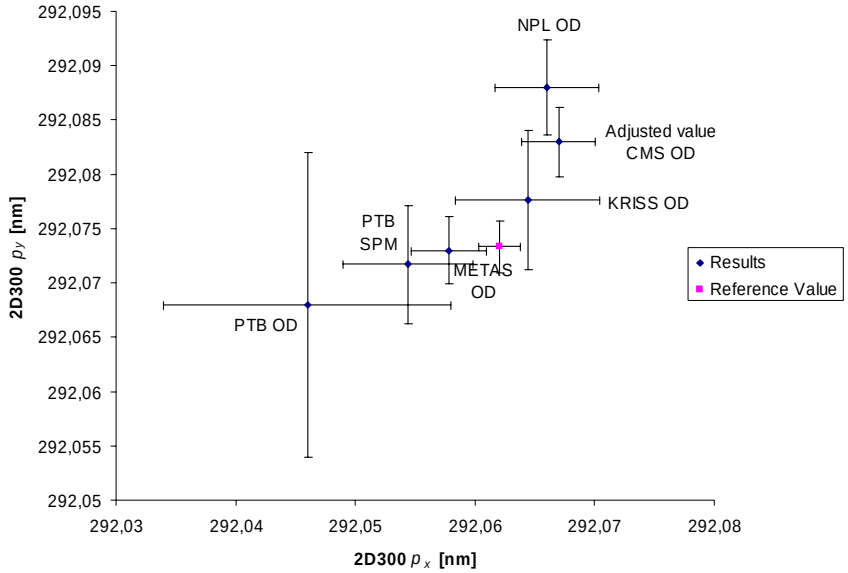

Figure 9 Measured pitch along the y-direction of the 2D300 grating as function of the measured pitch along the x-direction for the six most accurate measurements. The error bars are the reported combined standard uncertainties u_c .

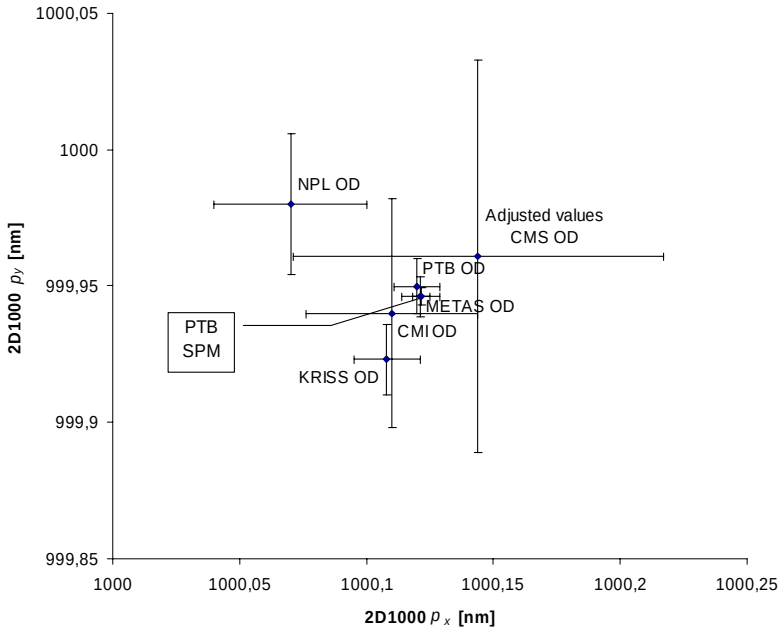

Figure 10 Measured pitch along the y-direction of the 2D1000 grating as function of the measured pitch along the x-direction direction for the six most accurate measurements. The error bars are the reported combined standard uncertainties u_c .

Summary of anoumalous results[e]

Measurand	Lab	En > 1 (based on final reference value)	Addendum submitted[a]	Corrected value[b]	Adjusted value[c]	Unex-plained En > 1	Total number of results
2D1000 x-direction	NPL SPM			En < 1[f]			20
	CMS OD				En < 1[f]		
2D1000 y-direction	CMI OD		En < 1[f]				20
	NPL SPM[d]	En=-1,15*		En < 1[f]			
	CMS OD				En < 1[f]		
2D1000 angle	METAS OD[d]	En = -13,79*			En < 1[f]		20
	CMI SPM	En = 1,37*				x	
	NIM SPM[d]	En = -2,11*				x	
2D300 x-direction	NPL SPM			En < 1[f]			18
	NIST SPM[d]	En = -2,27*		En < 1[f]			
	CMS OD[d]	En = 2,60*		En < 1*	En < 1[f]		
2D300 y-direction	NIST SPM [d]	En = -2,34*		En < 1[f]			18
	NPL SPM			En < 1[f]			
	NPL OD	En = 1,48*				x	
	CMS OD	En = 1,52*			En = 1,22*	x	
2D300 angle	PTB OD		En < 1[f]				16
	INRIM OD [d]	En = -48,52*		En < 1[f]			
Sum: 6	17	10	2	8	5	4	112

[a]Addendum certificate is recieved before any response from pilot lab was send regarding possible anomalous results.

[b]Corrected value is recieved after the laboratory has been inform that result "appear to be anomalous".

[c]Adjusted values is new calibration certificates recieved after the end of the comparison where all participants were informed about the results.

[d] Lab has been informed by the pilot lab that the (original) result "appear to be anomalous" before the results were known by the participants

[e] Summary of all (original) results which are either withdrawn by the laboratory or found to have an En > 1

[f] The corrected value is included in the calculation of the reference value. The (original) result is considered withdrawn from the calculation of the reference value

*En value is calculated with a plus sign in the denominator if the value is not included in the calculation of the reference value

Table 10 The table summarize the results which have been withdrawn by the Lab from the calculation of the reference value and the results which is omitted from the calculation because the En value is larger than one.

7 Analysis

7.1 Reference value and degree of equivalence

The calculation of the degree of equivalence is described in the technical protocol and summarized in the following for convenience.

For the comparison, the distribution of the measured values is assumed to be normal. The reference value x_{ref} is the weighted mean of all measurements x_i. The weights are $u(x_i)^{-2}$. With the given combined uncertainties $u(x_i)^{-2}$ and their effective degrees of freedom $\nu_{eff}(x_i)$, the $En(x_i)$ values for a confidence value of 95% are calculated. Measurements with En_{95} values larger than one have been omitted successively one by one for the calculation of the reference value. Finally, all values contributing to the reference value have En_{95} values ≤ 1. Some laboratories have supplied more than one measurement result achieved with different measuring techniques. Each such independent measurement contributes to the reference value.

$$x_{ref} = \frac{\sum_{i=1}^{n} u^{-2}(x_i) \cdot x_i}{\sum_{i=1}^{n} u^{-2}(x_i)}, \tag{3}$$

$$u_c(x_{ref}) = \left(\sum_{i=1}^{n} u^{-2}(x_i) \right)^{-1/2}, \tag{4}$$

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

$$U_{95}(x_{ref}) = u_c(x_{ref}) \cdot k_{95}, \text{ with } k_{95} = t_{95}(\nu_{eff}(x_{ref})) \tag{6}$$

$$En_{95}(x_i) = \frac{x_i - x_{ref}}{\sqrt{{U_{95}}^2(x_i) - {U_{95}}^2(x_{ref})}}, \tag{7}$$

In the *En* formula (7) the minus sign ("-") is used in the denominator for values contributing to the reference value but a plus sign ("+") is used for values not contributing to the reference value.

The reference values, the associated uncertainties and the degrees of equivalence *En* are given in **Table 4** to **Table 9**.

7.2 Optional questions

To scientifically access the role of the transfer standards and the issues which limit the accuracy of the measurements, the participants could answer some optional questions. The answers are included in the reports from the laboratories in the appendix.

If resources are available, the information could be gathered in tables and the results presented to for example CCL-WGDM and WGDM-DG7.

7.3 Consistency of results

The Birge ratio R_B is calculated to check the consistency of the estimated uncertainties with the variation of the different results. The Birge ratio is defined as:

$$R_B = \frac{s_{ext}}{s_{\text{int}}} \tag{8}$$

$$s_{ext} = \sqrt{\frac{\sum_i \left((x_i - x_{ref})/u_i\right)^2}{(n-1)\cdot \sum_i u_i^{-2}}} \tag{9}$$

$$s_{\text{int}} = u_c(x_{ref}) \tag{10}$$

where s_{ext} expresses a weighted standard deviation of the results x_i.

Including only results with En ≤ 1, all Birge ratios for the six measurands were in the range from 0.47 to 0.88 and thereby smaller than one, see **Table 11.** Therefore the reported results and their associated uncertainties can be considered consistent.

Measurand	R_b
2D1000 x-direction	0,72
2D1000 y-direction	0,82
2D1000 Angle	0,58
2D300 x-direction	0,82
2D300 y-direction	0,53
2D300 Angle	0,46

Table 11 Birge ratios

7.4 Omitted results or results with En > 1

Out of the 112 measurement results for the six measurands, 17 (original) results have either been removed from the calculation of the reference value- due to errors - or have been omitted because the En values were larger than one. These 17 (original) results have been reported by eight of the 12 participating labs, see **Table 10** for a summary of all anomalous results.

Ten of the (original) results reported have En values larger than one; six results have En values larger than two. However, the participating Labs have identified errors. For the calculation of the reference value they have

submitted a total of 15 corrected measurement values, see the certificates in the appendices. In the end only four results remain with an unexplained En value larger than one in the range from 1.4 to 2.1.

1. CMI SPM for 2D1000 has En = -1.37 (with a plus sign used in formula (7) see **Table 6**). The laboratory has been informed about a possible anomalous result. The result is only marginal outside the limits at a 95% confidence level and it could be due to normal statistical variation.

2. NIM SPM for 2D1000 has En = -2.11 (with a plus sign used in formula (7) see **Table 6**). The laboratory was informed that the result appeared to be anomalous but have not issued any corrected values or given any comments.

3. NPL OD for 2D300 in the y-direction has En = 1.48 (with a plus sign used in formula (7) see **Table 8**). The Lab finds that the comparison has shown a possible error in their measurements (laser), which they are investigating. There is no impact on the NPL CMC claims in this area since they are based on a claimed uncertainty approximately 10 times greater than the discrepancy.

4. CMS OD for 2D300 in the y-direction has En = 1.52 (with a plus sign used in formula (7) see **Table 8**). The lab has identified and error and increased the uncertainty relative to the original reported result but the corrected value remains with an En value larger than one (En = 1.22). The correlation between the x and y measurements for the six most accurate measurement are given in **Figure 9** and **Figure 10**.

8 Appendices

The appendices are distributed as a separate document to the participants as they are very large files. Each of the appendices A, B and C has a separate table of content.

1. **Appendix A - Results (Original)**
   Contains all the (original) results and reports from all participating laboratories including the uncertainty budgets and answer to the optional questions.

2. **Appendix B – Corrected and adjusted values**
   Contains documents regarding submission of corrected and adjusted values from each related laboratory:

   - A summary where the numerical error(s) and sources are explained.

   - A new signed report including appendix 6 with all the (corrected) measurement results for the particular grating and method.

   Reports have been submitted by most laboratory where the changes are clearly indicated by e.g. track changes. These reports are kept at the pilot lab for further access.

3. **Appendix C – Surface quality**
   Contains all documents reported by the participants regarding surface quality.

4. **Appendix D – Technical protocol**
   For completeness, the technical protocol is added to the appendix.