MITTATEKNIIKAN KESKUS

CENTRE FOR METROLOGY AND ACCREDITATION

Julkaisu J4/2001

EUROMET PROJECT 533

HIGH PRECISION ROUNDNESS

Final Report

Björn Hemming

Helsinki 2001

MITTATEKNIIKAN KESKUS
CENTRE FOR METROLOGY AND ACCREDITATION

Julkaisu J4/2001

Euromet Project 533

HIGH PRECISION ROUNDNESS

Final Report

Björn Hemming

Helsinki 2001

Contents

Abstract

An international comparison of geometrical roundness measurements using error separation has been arranged between five European laboratories. In order to test the error separation in high precision roundness measurements, a glass hemisphere with a low roundness error was used. Measurements were made in two directions: perpendicular to the axis of rotation and perpendicular to the spherical surface. The measured departure from roundness varied from 5.6 nm to 20 nm and the calculated $E_n < 1$. The reason for the big variation in values of departure from roundness is believed to be unstability of the artefact. However, by removing the 2nd harmonic component from the roundness curves, similar features in some details are seen when comparing originally differently shapes.

Keywords: Roundness measurement; Interlaboratory comparison; Error separation

1. Introduction

In the last decade two BCR high precision roundness comparisons have been made in Europe [1] – [3]. In the latter, the results showed very satisfactory agreement. However, since then, error separation capabilities have been developed also in Finland at VTT Manufacturing Technology, which took the initiative to organise a small high-precision roundness comparison, initially with three other laboratories.

Error separation is a mathematical method whereby the systematic error of an instrument is removed [4]. The roundness measurement instrument incorporates a rotary stage to enable a number of roundness measurements to be made with the component rotated relative to the instrument spindle between each measurement. Software enables separation of the instrument spindle and component errors from the data. In the classical multistep method the amount of rotation between the measurements is typically 36°.

However, the multistep method cannot completely separate the spindle systematic error from the roundness error of the work piece. That is, the separated error contains values of the KMth harmonics of its counterpart (K is a natural number, M is the number of indexings in 2π radians) [6]. Recently a new non-equal-step method was developed at NPL based on the full-harmonic error separation technique described in [6].

In order to test the error separation, it was decided that the reference would be a hemisphere with a low departure from roundness. Therefore errors and non-linearity associated with magnification of the transducer will not influence the results. The work of the BCR S(30) comparison was recognised and therefore; similar measurement guidelines were used.

During analysis of the results the co-ordinating laboratory moved from the Technical Research Centre of Finland (VTT) to Mikes (Centre for Metrology and Accreditation), but is still referred to as VTT in this report.

2. Participating laboratories

Five European laboratories participated in the comparison (Table 1). The hemisphere was transported by air as hand luggage.

Table 1. Participants and timetable.

Laboratory	Contact Person	Measurement Date
VTT Manufacturing Technology, Espoo, FI VTT 1	B. Hemming	17.09.1998
Eidgenössisches Amt fur Messwesen, METAS Wabern, CH	R. Thalmann	26.11. – 27.11.1998
VTT 2		12.12.1998
Sveriges Provning- och Forskningsinstitut, SP Borås, SE	M. Frennberg	17.12. – 18.12.1998
Physikalisch-Technische Bundesanstalt, PTB Brauschweig, DE	F. Luedicke	10.05.1999
VTT 3		08.06.1999
National Physical Laboratory, NPL, Teddington, UK	D. Flack	16.06. - 17.06.1999
VTT 4		26.07.1999

3. Circulated standard

The standard was a hemispherical glass roundness standard (code No. 112/2324, serial No. 960F) manufactured by Taylor Hobson Ltd. The calibration certificate 25740 issued by Taylor Hobson on 30th October 1997 gives a roundness error of 12 nm at 1-150 filter. The diameter of the hemisphere is approximately 50 mm.

4. Measurement instructions

All participants had the roundness measurement instrument Talyrond 73 manufactured by Rank Taylor Hobson. Each laboratory was required to use its own error separation technique to remove the contribution of the spindle error. As in previous comparisons, departure from roundness was to be evaluated with reference to the least squares circle (LSC). The laboratories were asked to make a measurement perpendicular to the axis of rotation (A direction) and perpendicular to the spherical surface (S direction). The plane of measurement is 3 mm above the top of the mount. Further requirements are given in the guidelines in Appendix 1. No harmonics were required. The measurement parameters used by the participants are shown in Table 2. The fastening

Table 2. Measurement parameters.

Laboratory	Instrument Holding method	Method	No of points Meas. Force Stylus & radius	Filtering	Detail	Result given
SP	Talyrond 73 Purchased 1989 Thread on hemisphere mount	RTH error separation software.[1] 10 steps 4 run/step	50 (512 reduced to 50) 100 mN Hatchet 6.4 mm (S orientation) Ball 0.79 mm (A orientation)	Analogue prefilter 2RC	S unfiltered	
					S 1-500 filter/unfiltered	x
					S 1-50 filter	x
					S 1-15 filter	x
					A unfiltered	
					A 1-500 filter	
					A 1-50 filter	x
					A 1-15 filter	
METAS	Talyrond 73 Purchased 1966 Upgraded 1991 Adhesive gum	METAS multistep 10 steps 3 run/step	2000 5-15 mN Sphere Ruby 2mm	Phase-corrected 2RC digital	S unfiltered	x
					S 1-500 filter/unfiltered	x
					S 1-50 filter	x
					S 1-15 filter	x
					A unfiltered	x
					A 1-500 filter	x
					A 1-50 filter	x
					A 1-15 filter	x
PTB	Talyrond 73 and Moore index table Adhesive gum	Multistep 10 steps 3 run/step	4096 30 mN Ruby, 0.5 mm	Phase-corrected 2RC Gauss filter digital	S unfiltered	
					S 1-500 filter/unfiltered	
					S 1-50 filter	
					S 1-15 filter	
					A unfiltered	
					A 1-500 filter/unfiltered	x
					A 1-50 filter	x
					A 1-15 filter	x
NPL	Talyrond 73 developed by NPL and RTH Thread on hemisphere mount	Non-equal step[2]	2000 50 mN Hatchet 6.4 mm (S-orientation) Ball 1121113 0.79 mm (A orientation)	Gauss filter digital	S unfiltered	
					S 1-500 filter/unfiltered	[3]
					S 1-50 filter	x
					S 1-15 filter	x
					A unfiltered	
					A 1-500 filter/unfiltered	[3]
					A 1-50 filter	x
					A 1-15 filter	x
VTT	Talyrond 73 Adhesive tape	Multistep 10 steps 5 run/step	2000 10-20 mN VTT 1 and VTT 2[4] Hatchet 6.4mm/0.4mm VTT 3 and VTT 4 Ball 0.79 mm	Phase-corrected 2RC digital	S unfiltered	x
					S 1-500 filter/unfiltered	x
					S 1-50 filter	x
					S 1-15 filter	x
					A unfiltered	x
					A 1-500 filter/unfiltered	x
					A 1-50 filter	x
					A 1-15 filter	x

[1] New measurement made for each filter due to data processing limitations in the instrument.
[2] One multistep measurement also made in the A orientation.
[3] Result given for 150/unfiltered and will be included in the result tables for 1-500 filter and 1-50 filter for comparison.
[4] It should be noted that hatchet tip is not suitable for A orientation.

5. Stability of the standard

During the comparison an oval shape appeared and disappeared on the hemisphere, temporarily increasing departure from roundness by about 10 nm. It is difficult to give a reason for this ovality. One reason might be changes in fixation due to grease on the identification paper under the hemisphere. To study the development of this ovality the 2nd harmonic was chosen to characterise the shape. Data files of 1-50 filtered results were analysed[1] (table 3). There is a considerable change in the hemisphere as seen in the amplitude of the 2nd harmonic (figure 1). Figures 2 and 3 show a "stretching" of the hemisphere towards angles 140° and 340°.

Table 3. Variation of the 2nd harmonic of 1-50 filtered results.

	2nd Harmonic component	
	S Orientation	A Orientation
VTT 1	3.3	
METAS	0.5	1.5
VTT 2	2.1	3.2
SP	4.2	
PTB		6.5
VTT 3	4.8	6.5
NPL	3.2	3.5
VTT 4	1.5	0.5
Variation	4.3	6.0

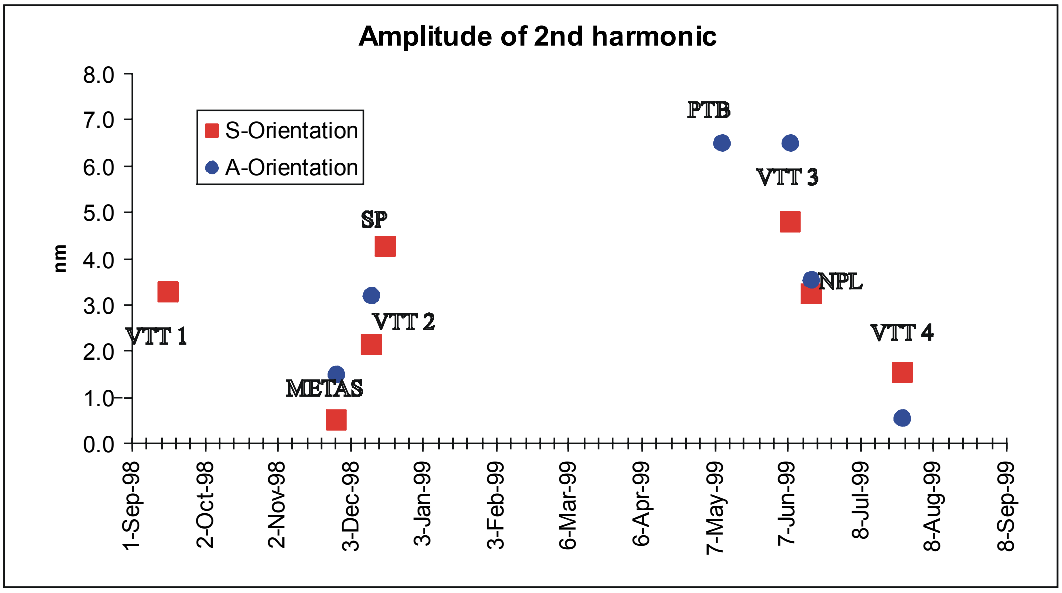


Figure 1. Variation of the 2nd harmonic of 1-50 filtered results plotted on the time scale of the circulation.

[1] The NPL data were 1-150 filtered.

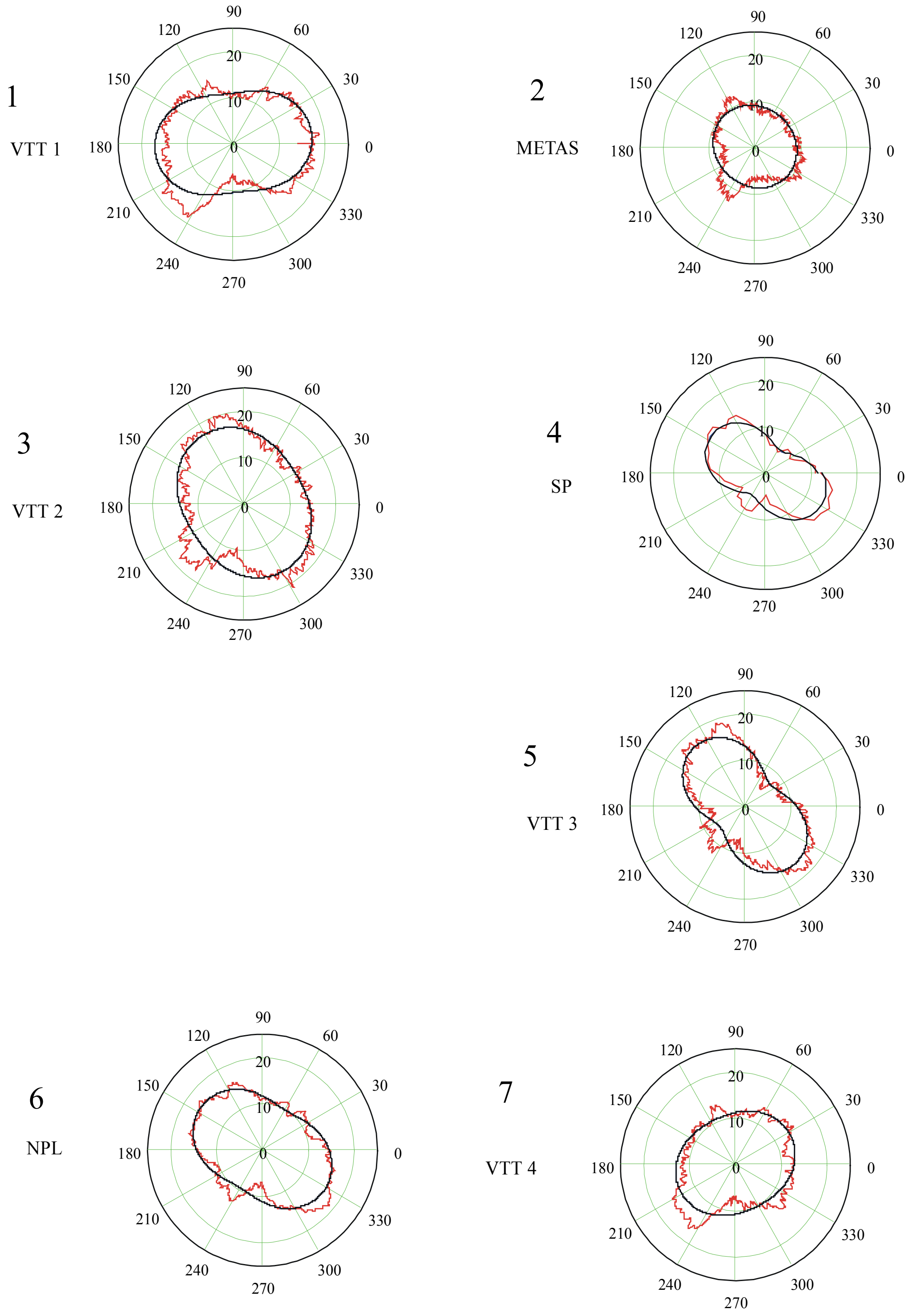


Figure 2. 1-50 filtered results of the S orientation in order of circulation together with the 2nd harmonic. The supplied unfiltered METAS data is filtered by a running median (n=9) filter. The curve of SP results is plotted with 50 points.

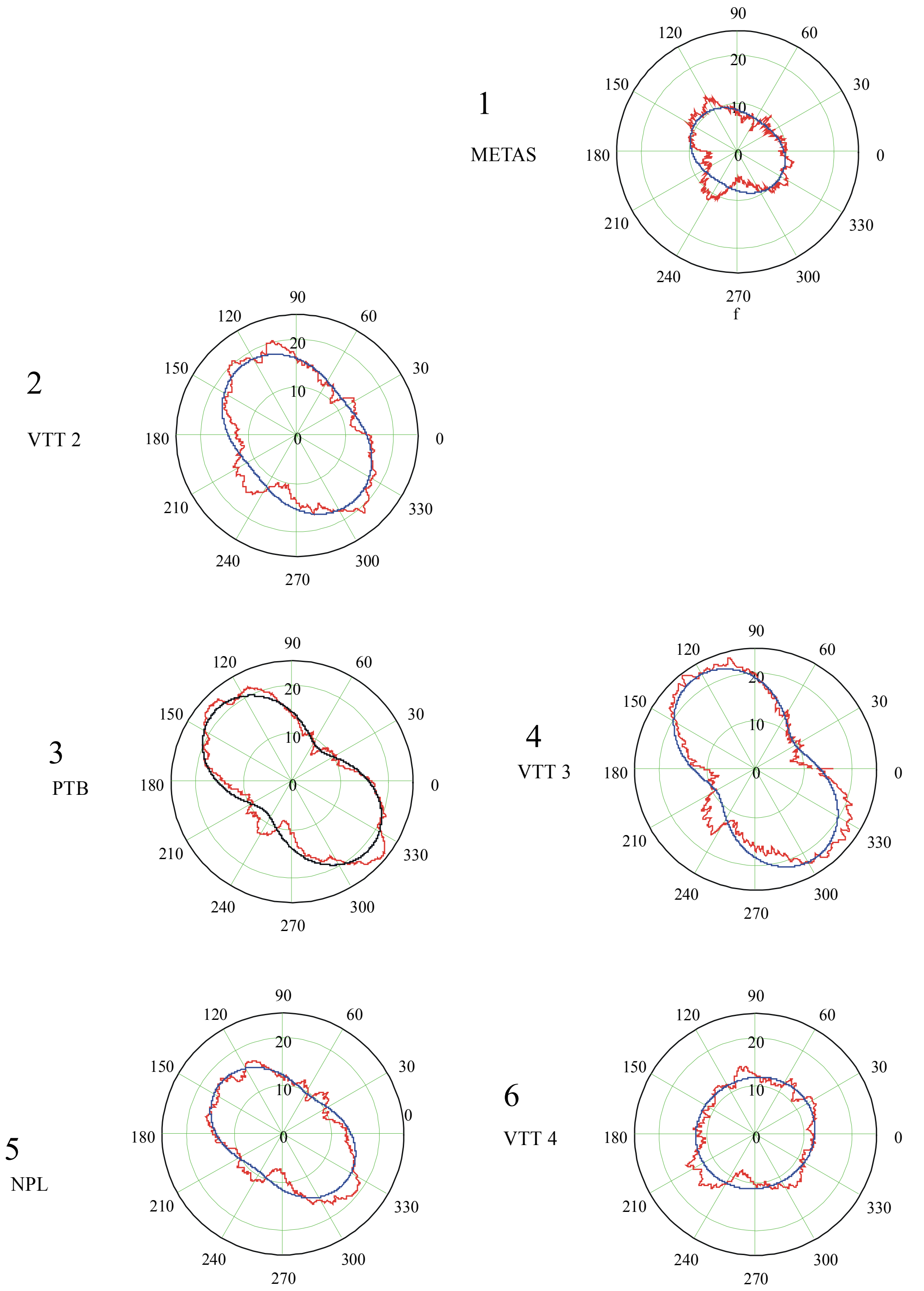


Figure 3. 1-50 filtered results in order of circulation of the A orientation together with the 2nd harmonic. The supplied unfiltered METAS data is filtered by a running median (n=9) filter.

Another explanation for the different shapes could be the different angular horizontal orientations. However, between measurements in the directions denoted A and S, the table is also adjusted vertically. Therefore, if the reason for the different shapes lay in the measurement directions at different heights, one would also expect the shapes to differ for orientations A and S.

Unfortunately there is no previous history of calibration results for the hemisphere before measurement VTT 1, except the calibration certificate from Taylor Hobson. As mentioned in an earlier chapter the Taylor Hobson certificate gives a departure of roundness of 12 nm, which is very close the VTT 1 value. Therefore the stability of the hemisphere seems to have been good before the comparison.

By removing the 2nd harmonic component from the roundness curves, similar, even sub-nanometric features in some details are seen when comparing originally differently shaped results such as NPL and VTT 4 or METAS and VTT 3 (figure 4). The curves of VTT are plotted in figure 5, and in figure 6 with the 2nd harmonic component removed. In figure 5 the curves VTT 1 and VTT 2 differs with about 14nm from each other when looking at points at 45° and 105° or 290° and 195°. Figure 6 shows good reproducibility of the curves when the 2nd harmonic component is removed. For each angle there are four points and the standard deviation for the points at all 2000 nominal angles were calculated. The mean value of the standard deviation was 0.76nm for the curves of figure 6.

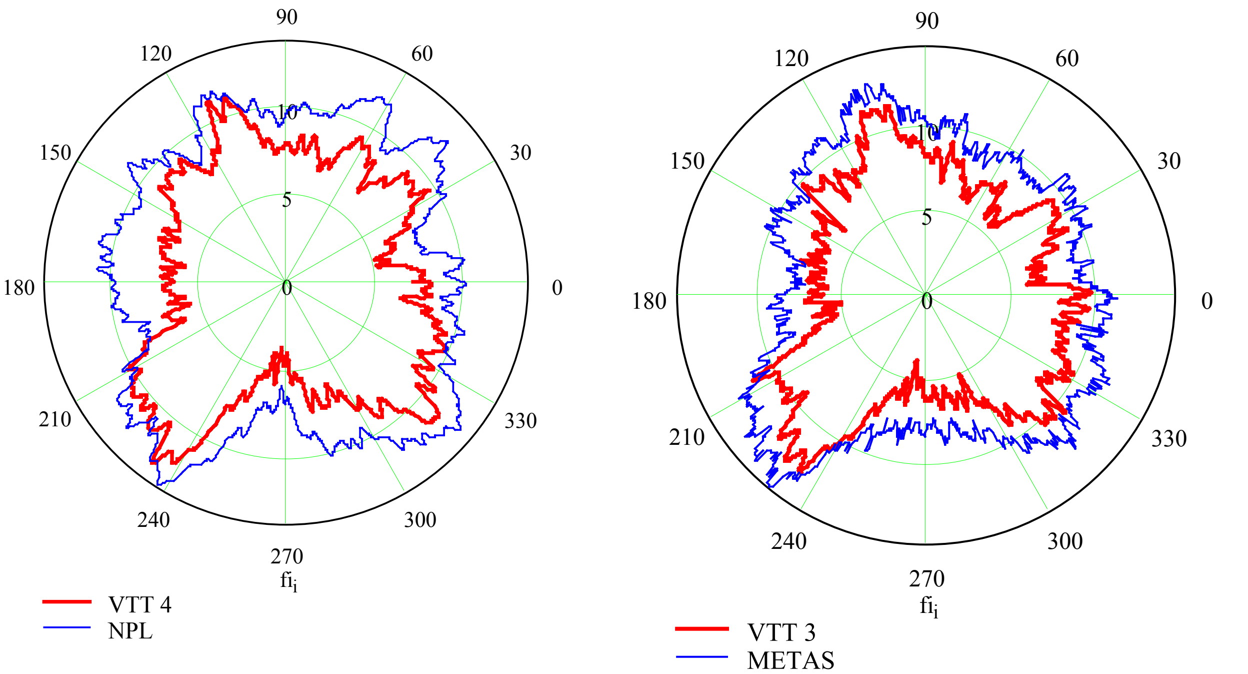


Figure 4. The 2nd harmonic component removed from the roundness curves NPL together with VTT 4, and METAS together with VTT 3 for the 1-50 filtered results of the S orientation. The difference between VTT 4 and NPL curves is about ±2nm, and between VTT 3 and METAS curves about ±1.5nm. The METAS curve is plotted with a phase shift of 11°.

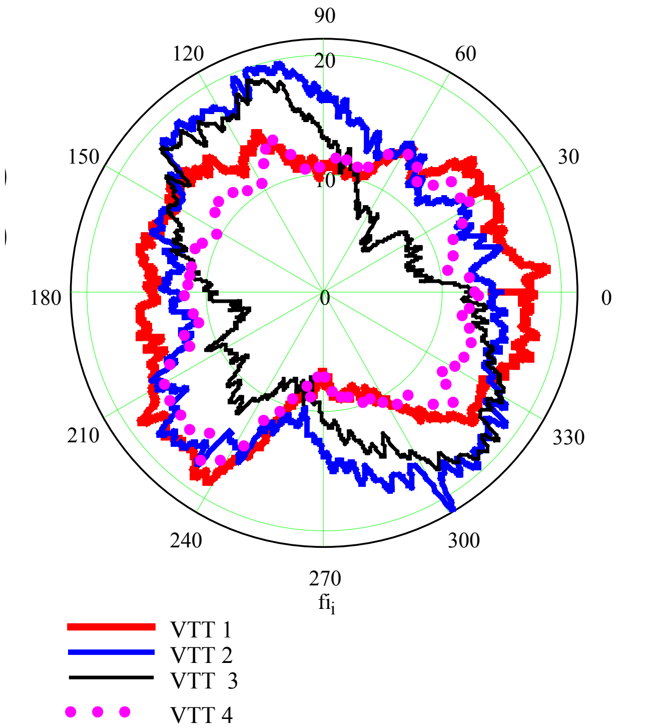


Figure 5. 1-50 filtered results of the S orientation by VTT.

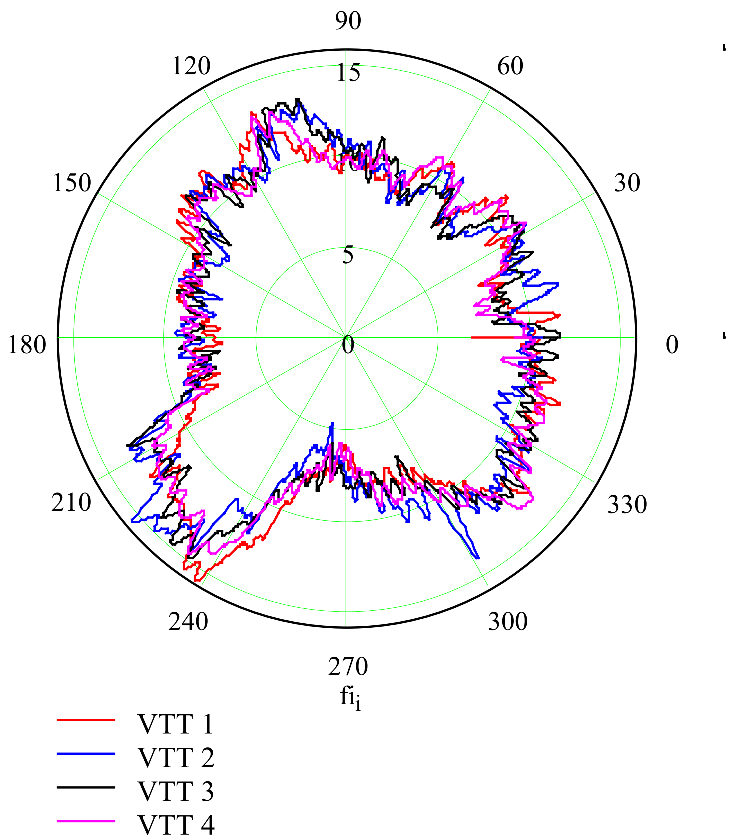


Figure 6. 2nd harmonic component removed from the 1-50 filtered results of the S orientation roundness curves of VTT.

For the S direction, the departure from roundness between the first and last measurements made by VTT was about 2 nm. For the A direction the roundness value from the last measurement was about 4 nm lower than the first.

A small scratch in the standard measurement plane was found at SP.

6. Reference value

For many cases of measurement directions and filtering conditions, the results from VTT are over-represented. In the analysis, a non-weighted mean value $\mathbf{x_{ref}}$ is used as reference and the results of VTT were averaged and treated as one participant when calculating the mean (tables 4 and 5).

Another interesting approach would be to look at the time scale of the circulation and to compare PTB with VTT 3, SP with VTT 2 and NPL with the average of VTT 3 and VTT 4. This approach was abandoned because it would lead to somewhat arbitrary results depending on when a VTT measurement was made and on the decision how to use closest one or closest two VTT measurements as reference.

The standard uncertainty of the reference value $\mathbf{u(x_{ref})}$, is calculated by combining the uncertainties of the laboratories with an estimate of the unstability of the artefact $\mathbf{u(x_{art})}$. The combined uncertainty $\mathbf{u(x_{LAB})}$ of the laboratories is

$$u(x_{LAB}) = \frac{1}{\sqrt{n}}\sqrt{\sum_{i=1}^{n} u(x_i)}\ , \qquad (1)$$

where $\mathbf{u(x_i)}$**,** (k=1) is the reported uncertainty. The value of $\mathbf{u(x_{LAB})}$ is 3.92 nm for the A-orientation and 4.00 nm for the S-orientation.

The unstability of the artefact is determined from table 3 and by looking at figure 2 and figure 3. The measurement VTT 3 shows the largest stretching of the reference measurements towards angles 140° and 340°. The measurement VTT 4 shows a stretching in the perpendicular direction. The unstability of the artefact for A-orientation evaluated from VTT results in table 3 and figure 2 is ±7nm (sum of harmonic amplitudes 6.5nm for VTT 3 and 0.5nm for VTT 4). For S-orientation the unstability of the artefact is ±6.3nm (sum of 4.8nm for VTT 3 and 1.5nm for VTT 4). A rectangular distribution is assumed and $\mathbf{u(x_{art})}$ is calculated by dividing the variations with $\sqrt{3}$. The standard uncertainty of the reference value $\mathbf{u(x_{ref})}$ is calculated using

$$u(x_{ref}) = \sqrt{u(x_{LAB})^2 + u(x_{art})^2}\ . \qquad (2)$$

It is assumed that the degree of freedom is large and the calculated expanded uncertainty $\mathbf{u(x_{ref})}$, (k=2) for the reference value is 11.3nm for A-orientation and 10.8nm for S-orientation.

7. Results and discussion

The reported results of peak-to-valley departure from roundness are shown in tables 4 and 5 and in Appendix 2. The reported curves are shown in Appendices 3-7. The measurement procedures of the laboratories are described in Appendix 8. The standard deviation for the mean was 2.1-2.8 nm for the S orientation and 4-5 nm for the A orientation. The largest E_n value was 0.5 for departure from roundness. Received data files of 1-50 filtered results of the S orientation are plotted in figure 7.

The VTT1, METAS and VTT4 curves at the start and end of the comparison have a similar shape and quite low values of departure from roundness. The most apparent feature is a local maximum of about +3nm in the area from 210° to 240°. Midway in the comparison there are much higher values for departure from roundness from PTB and VTT3, and similarities in the shapes with a local maximum of about +8nm at 120° – 140, suggesting a change in the hemisphere. The shapes of VTT2, SP and NPL have similarities to both the above types of shape. Looking at the values of departure from roundness at a time scale reveals the following. The measurement of PTB is close to the measurement of VTT 3 both in time and as departure from roundness. The measurement of NPL is in the middle between VTT 3 and VTT 4 both in time and as departure from roundness.

The radial error of the spindle removed by the error separation method is of the order of 25 nm. Contrary to previous high precision roundness comparisons, in this comparison the departure from roundness of the hemisphere is in most cases smaller than the radial error of the spindle.

In a previous comparison during 1993 – 1994, a systematic dependence on the measuring direction was found theoretically to be a cosine effect (1.5 nm when the mean of the departure from roundness was 20 nm – 25 nm depending on filtering) for an angle of 20° [1]. In this comparison the values for departure from roundness for the A direction were on average 0.6 nm bigger than for the S direction. This value correlates well with the previously reported cosine effect.

Having a coordinator travel personally with the reference as hand luggage ensured safe circulation of the object between participants. Unfortunately, the time available for measurements was not enough for participants to make all the requested measurements. The coordinator regrets that the arrangements for the circulation did not permit all participants to make all measurements.

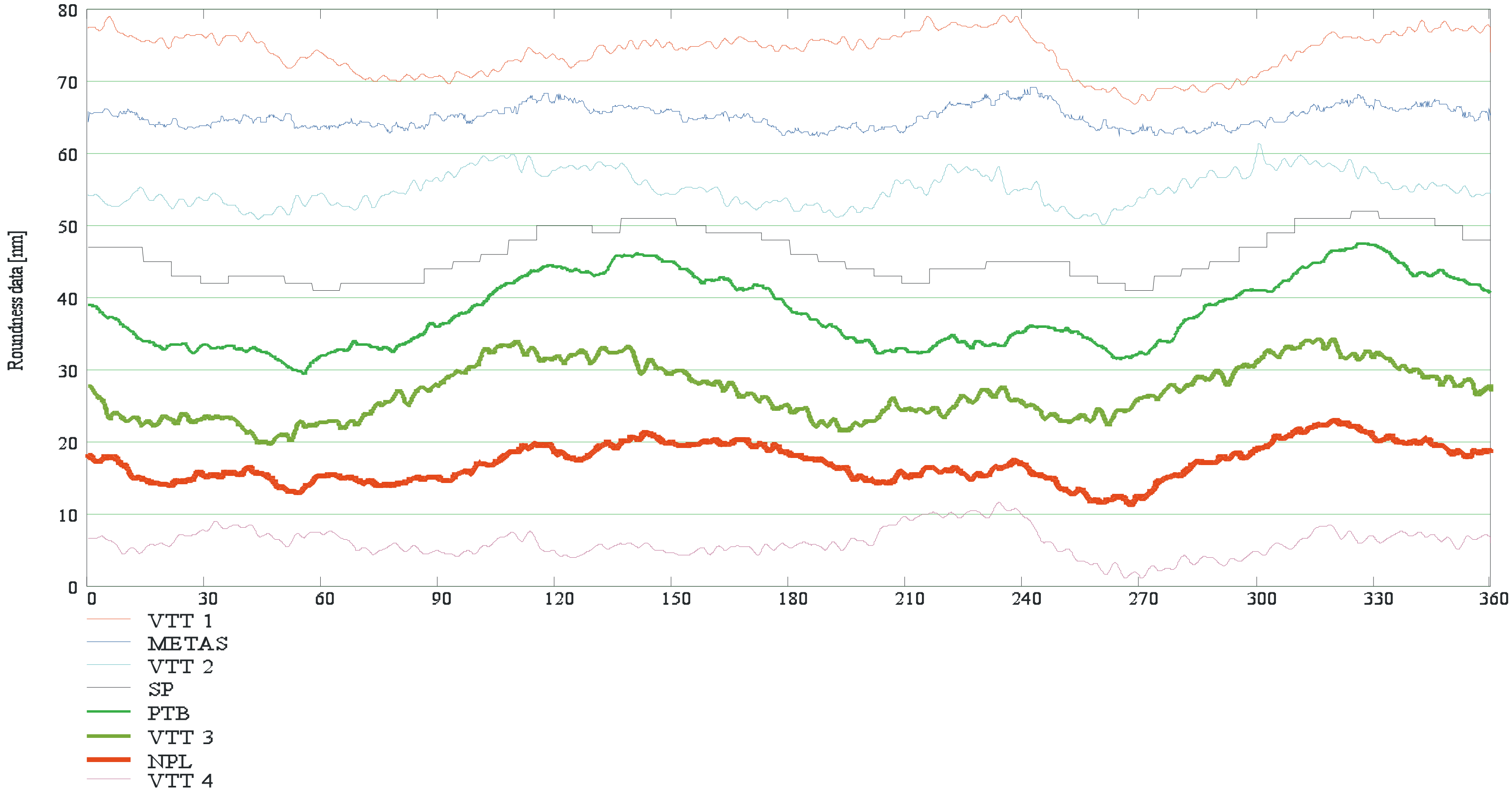
Table 4. Results for direction S.

LAB	Uncertainty [nm]	Unfiltered			1-500 Filter			1-50 Filter			1-15 Filter		
		Departure from roundness	Deviation from Ref [nm]	En	Departure from roundness	Deviation from Ref [nm]	En	Departure from roundness	Deviation from Ref [nm]	En	Departure from roundness	Deviation from Ref [nm]	En
VTT 1	12	13.1	2.0	0.12	13.1	1.3	0.09	12.3	1.6	0.10	11.3	2.2	0.13
METAS	6	9.1	-2.0	-0.16	8.7	-3.1	-0.25	6.5	-4.3	-0.34	5.6	-3.5	-0.29
VTT 2	12	12.9	1.8	0.11	12.9	1.1	0.07	11.3	0.6	0.04	8.6	-0.5	-0.03
SP	5				13	1.2	0.10	12	1.3	0.11	11	1.9	0.16
PTB													
VTT 3	12	15.5	4.4	0.27	15.5	3.7	0.23	14.6	3.9	0.24	14	4.9	0.30
NPL	7.1				12.2	0.5	0.04	12.2	1.5	0.11			
VTT 4	12	11	-0.1	-0.01	11	-0.8	-0.05	10.5	0.3	-0.01	9.3	0.2	0.01
VTT Average		13.1			13.1			12.3			10.8		
Arithmeti c average		11.1			11.8			10.8			9.1		
St. Dev		2.8			2.1			2.8			3.1		

Table 5. Results for direction A.

LAB	Uncertainty [nm]	Unfiltered			1-500 Filter			1-50 Filter			1-15 Filter		
		Departure from roundness	Deviation from Ref [nm]	En	Departure from roundness	Deviation from Ref [nm]	En	Departure from roundness	Deviation from Ref [nm]	En	Departure from roundness	Deviation from Ref [nm]	En
VTT 1													
METAS	6	10.9	-0.9	-0.07	10.3	-3.6	-0.28	7.4	-5.1	-0.39	6.2	-5.3	-0.41
VTT 2	12	12.2	0.4	0.02	12.2	-1.7	-0.10	11.8	-0.7	-0.04	11	-0.5	-0.03
SP								12	-0.5	0.04			
PTB	5				20	6.1	0.50	18	5.5	0.45	17	5.5	0.45
VTT 3	12	17.8	6.0	0.36	17.8	3.9	0.24	17.1	5.3	0.28	15.8	4.3	0.26
NPL	6.4				12.5	-1.4	-0.11	12.5	0.0	0.01			
VTT 4		8.2	-3.6	-0.22	8.2	-5.7	-0.34	7.8	-4.7	-0.27	6.8	-4.7	-0.28
VTT Average	12	12.7			12.7			12.5			11.2		
Arithmeti c average		11.8			13.9			12.5			11.5		
St. Dev		1.3			4.2			3.8			5.4		

Figure 7. Curves of 1-50 filtered results for the S-orientation shifted to permit visual comparison. Curves are plotted downwards in the same order as in the circulation (uppermost curve is VTT 1 and lowermost VTT 4). [1]



[1] The plotted NPL data were 1-150 filtered. PTB 4096 points for A-direction reduced to 2000 points by plotting every second point up to 4000, and omitting the last 95 points, leading to a stretching of the curve by 8.6 degrees. Ofmet data filtered for plotting purposes by running median (n=9)

8. Conclusions

The trend in shape and 2[nd] harmonic component suggest unstability in the hemisphere, making it somewhat difficult to draw conclusions. However, the differences between the laboratories are still within the uncertainties of the laboratories. The largest E_n value for departure from roundness is 0.5 .

The measured departure from roundness varied from 5.6 nm to 20 nm. By removing the 2nd harmonic component from the roundness curves, similar features in detail are seen when comparing originally differently shaped curves. Therefore, the comparison shows that error separation works for a hemisphere with a departure from roundness below the radial error of the spindle. The comparison did not show difference between departure from roundness measured with the non-equal-step method and departure of roundness measured with the equal-step method.

The main differences in the measurement routine of the participants were in implementation of the error separation algorithm, filtering, and the rotary table for measurement of the component. The most recent developments in roundness measurements have been in the field of mathematical methods and software, and therefore a software comparison using generated data files is suggested.

Acknowledgment

The author wishes to thank Mr. Heikki Lehto and Dr. Antti Lassila for advices and help during the preparation of the report.

References

1. Frennberg, M., Sacconi, A. Intercomparison of high accuracy roundness measurements Final Report. Report EUR 16217 EN. Brussels, Community Bureau of Reference, 1996.

2. Sacconi, A.. Intercomparison of high accuracy roundness measurements. Report EUR 14662 EN, Brussels. Community Bureau of Reference. 1993.

3. Sacconi, A., Pasin, W. An intercomparison of roundness measurements between ten European national standards laboratories. Measurement, 13, 1994.

4. Whitehouse, D.J. Some theoretical aspects of error separation techniques in surface metrology. Journal of Physics E. vol 9/1976.

5. Linxiang, C. The measuring accuracy of the multistep method in the error separation technique. Journal of Physics E 22 (1989) 11.

6. Linxiang, C., Hong, W., Xiongua, L. and Qinghong, S. Full-harmonic error separation technique. Measurement Science & Technology 3 (1992) 12.

7. Frennberg, M. Kalibrering av rundhetsnormaler. Swedish National Testing and Research Institute. SP Rapport 1991:22. 27 p.

8. Thalmann, R., Spiller, J. Rundheitsmessung mit nanometer-Genauigkeit. METAS*Info*. Vol. 1 No. 2/1994.

APPENDIX 1 (1/5)

Measurement instructions

The same guidelines for measurement of the hemisphere were used as in [1] where applicable.

The following four pages are copied from [1].

BCR-project: Roundness intercomparison II Guidelines

1 Introduction

After the first roundness intercomparison financed by BCR and piloted by IMGC, it was decided to make a second intercomparison on the highest level of accuracy.

One reason for this is that more European laboratories now have error separation techniques which will make the intercomparisons more valuable.

Another reason is the need to further investigate the stability of the standards and to try to improve them.

This time the intercomparison is copiloted by IMGC and SP. SP is coordinator and responsible for the circulation.

The intercomparison consists of three standards, one hemisphere and two complete spheres. The hemisphere is of a common commercial type (RTH) and the two spheres have been procured by IMGC.

2 Definition of Measurements

2.1 The circulating standards are:

- Hemispherical glass roundness standard, code no. 112/436 ser. no 634 E, Manufacturer: Rank Taylor Hobson Ltd.

- Two complete spheres (about 30 mm dia) with their holding mount, identified as:
  IMGC 1, silicon nitride (black sphere)
  IMGC 2, zirconium oxide (white sphere).

2.2 Each laboratory shall use an error separation measurement method and its own cleaning and clamping procedures. A full description of them shall be given in the report.

2.3 Departures from roundness are to be evaluated with reference to the least squares circle (LSC) and, as an option, with reference to the minimum zone circles (MZC).

2.4 Each measurement shall be accompanied by its relevant plot (LSC at 500 upr).

2.5 Filtering conditions: Prefiltering (analogue filter) 500 UPR (or "unfiltered"), 50 UPR and 15 UPR. Other filtering procedures are optional.

2.6 Hemisphere

2.6.1 Angular positioning: the reference mark (black mark on the mount) should be aligned with the 0° reference position of the rotating element.

2.6.2 Plane of measurement: at 3 mm above the top of the mount.

2.6.3 Direction of measurement: normal to the spherical surface or perpendicular to the axis of rotation.

2.6.4 Preferred magnification in the graphical representation: 200 000 x or more.

2.6.5 A repeatability test (three or more measurements) should be provided. The workpiece is to be taken off the instrument between measurements.

2.7 Spherical standards

2.7.1 Angular positioning: the reference mark (engraved line on the top surface of the mount) should be aligned with the 0° reference position of the rotating element.

2.7.2 Plane of measurement is the equatorial plane of the sphere. **It is very critical that the feeler is set precisely at the equatorial plane,** because the shape of the spheres varies slightly. Please use some adjustment device to find the maximum point. The feeler should be positioned within 0,1 mm from the equatorial plane.

2.7.3 Preferred magnification in the graphical representation: 200 000 or more for IMGC 2 (white), 20 000 for IMGC1 (black).

2.7.4 A repeatability test (three or more measurements) should be provided. The workpiece is to be taken off the instrument between measurements with a re-location of the measured profile.

2.8 Harmonic analysis

You are also invited to make harmonic analysis of the measured profile of each standard. (This is optional.) If you have this possibility please report amplitude and phase angle (with respect to the ingraved line on the standard) for each component.

3 Data reporting

3.1 Each participant will produce a written report to be submitted to the pilot laboratory (SP, Borås) and to IMGC within one month after termination of measurements.

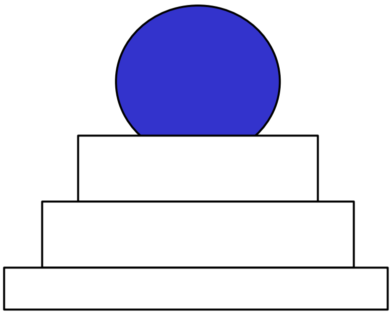
3.2 In order to summarize the measuring set-ups and conditions, each laboratory is asked to fill in the following list:

1. Rotating workpiece or rotating probe
2. Rotational speed (rpm), Direction of rotation (CW or CCW)
3. Number of measured values per revolution
4. Filtering conditions (analogue or digital, prefiltering, software filtering)
5. Plotting magnification
6. Error separation technique (Multistep/otherwise), details (Number of steps etc)
7. Stylus: lever type or plunger type, dimensions
8. Stylus static force (gaging force)
9. Ball tip: material, diameter
10. Transducer type.

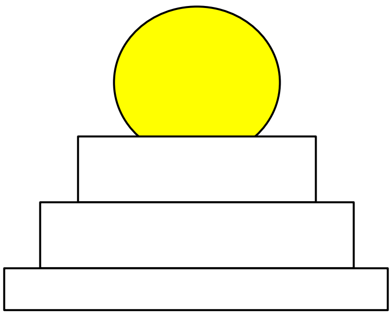
3.3 The report must also include:

1. List and identification of the instruments
2. Description of measurement methods
3. Traceability to primary standards (calibration devices and procedures)
4. Details on cleaning and clamping
5. Date and hour of measurements
6. Ambient temperature and its variation during measurements
7. Number of replications for each measurement
8. Table summarizing the final results of all measurements (see tables in **9**)
9. Statement of the uncertainty of all results (with an analysis of individual contribution), following BIPM recommandations, with k = 2.
10. Any additional results concerning optional measurements
11. Any additional detail, comment or suggestion useful for the interpretation of results as well as on the experience gained with this exercise.

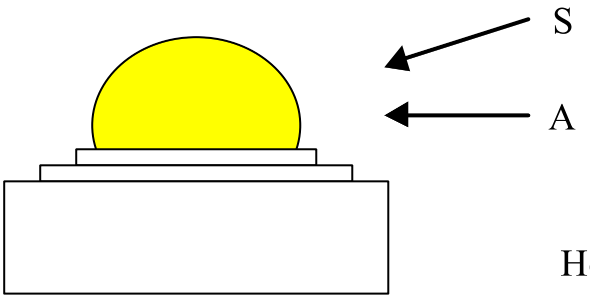
CIRCULATED STANDARDS



IMGC1, Silicon Nitride



IMGC2, Zirconium Oxide



Hemisphere RTH 634E

Appendix 2. Results

All the reported results are the peak-to-valley departure from roundness determined at each filtering condition, in relation to the centre of the least squares circle (LSC). Each value is followed by its expanded uncertainty at 95% confidence level evaluated by each participant (Figures 1-8). When a laboratory did not contribute a specific result the relevant space is left empty.

Figure 1. Results for direction S, unfiltered.

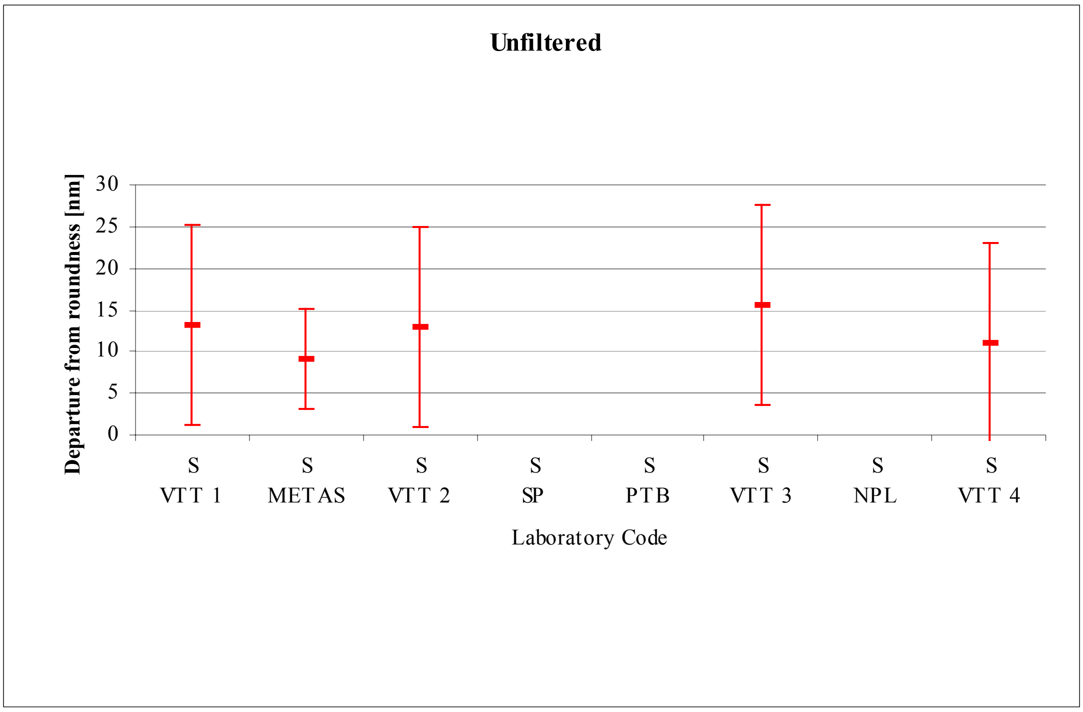


Figure 2. Results for direction S, 1-500 filter.

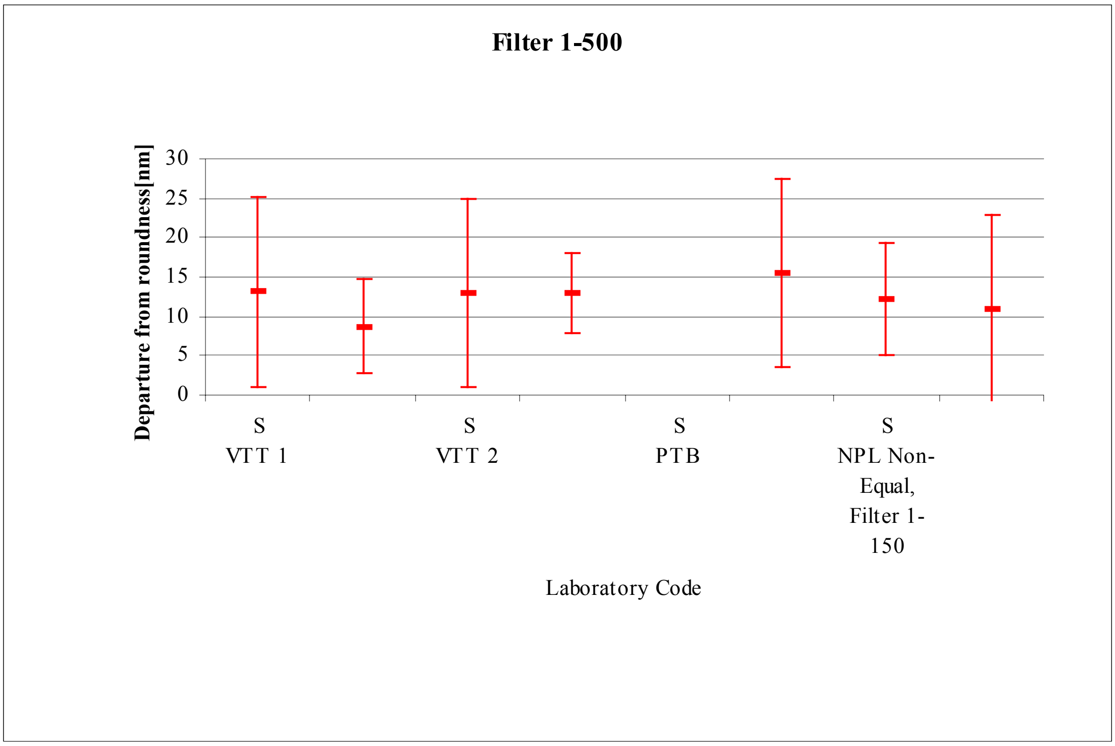


Figure 3. Results for direction S, 1-50 filter.

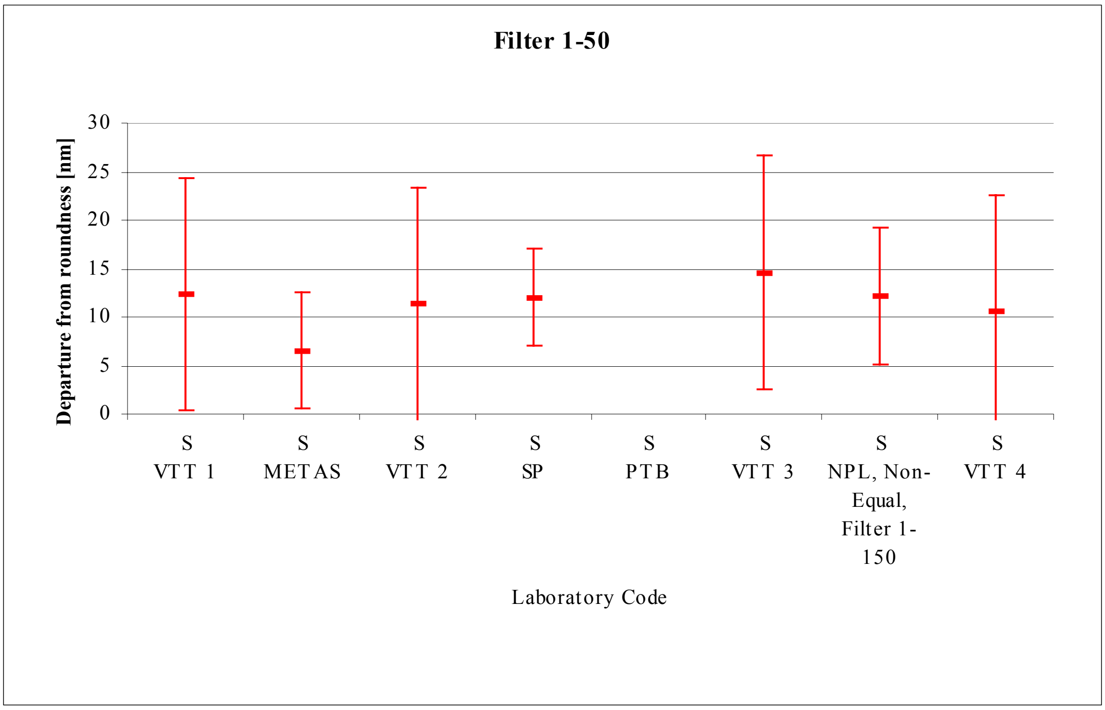


Figure 4. Results for direction S, 1-15 filter.

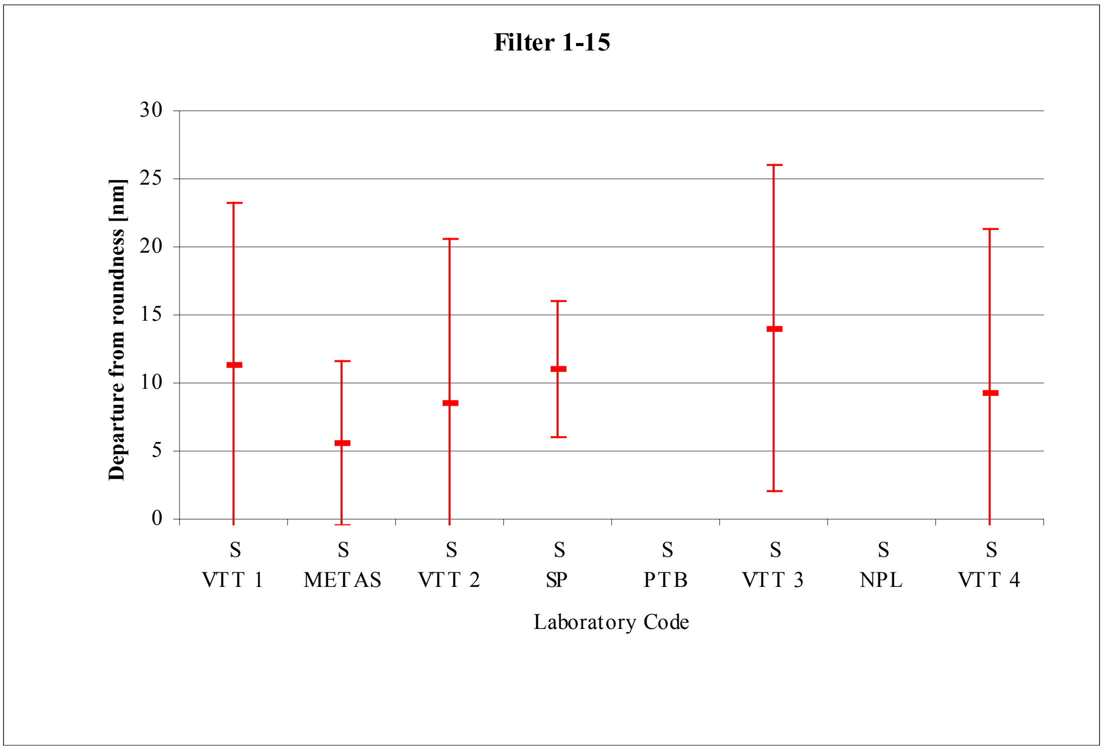


Figure 5. Results for direction A, unfiltered.

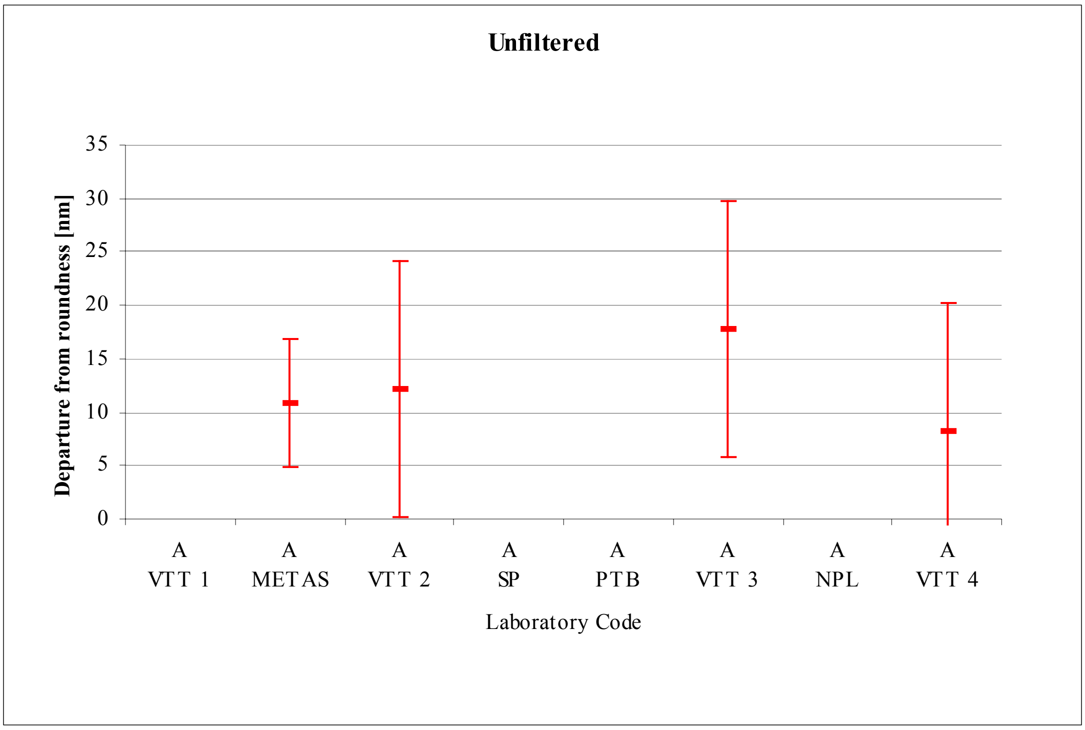
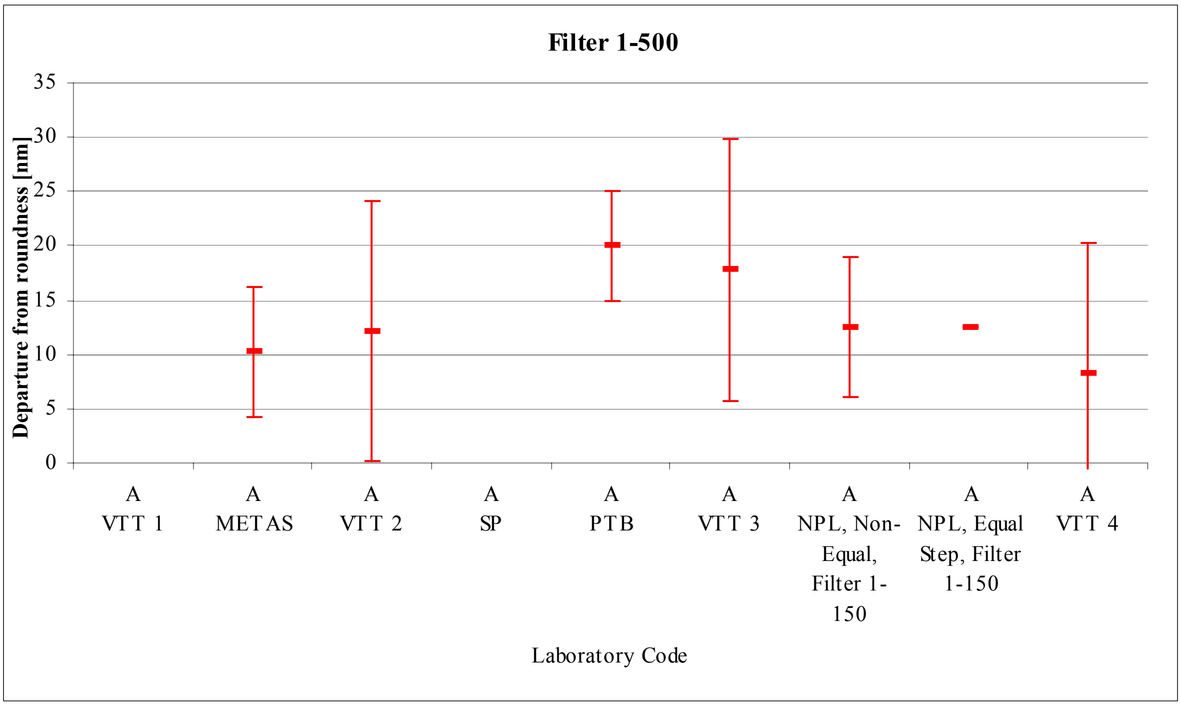


Figure 6. Results for direction A, 1-500 filter[1].



[1] Uncertainty not reported for NPL equal Step method

Figure 7. Results for direction A, 1-50 filter.[1]

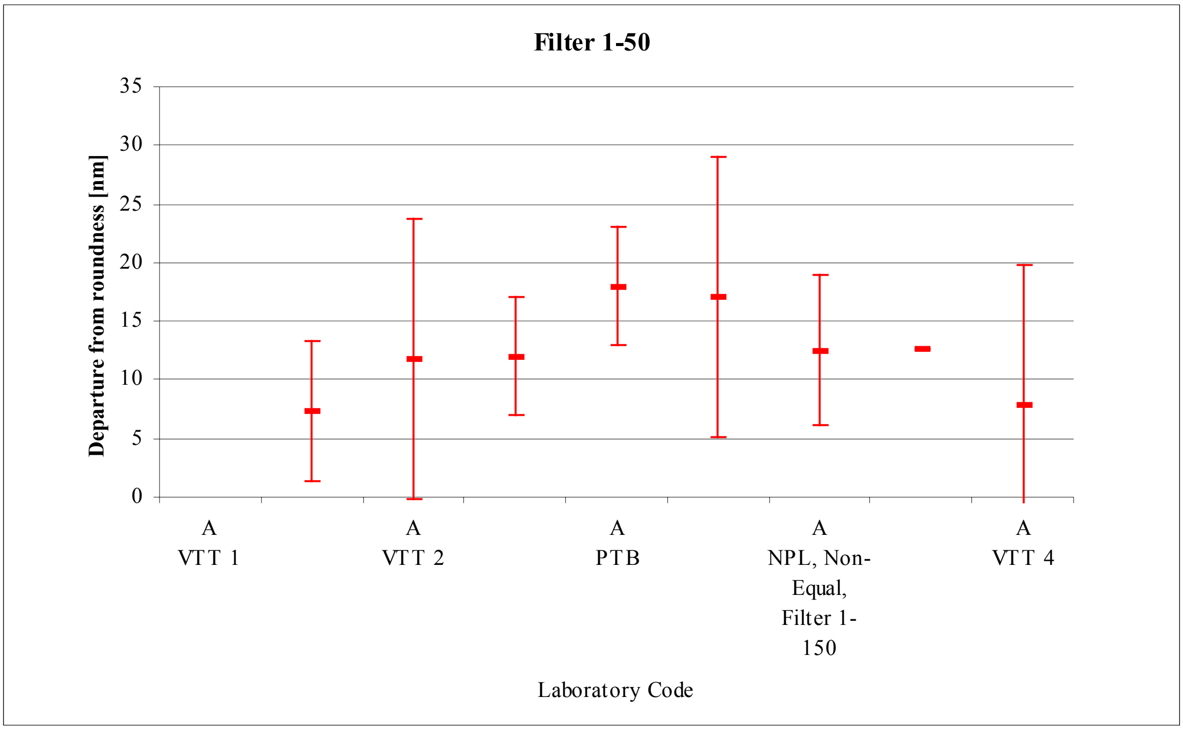
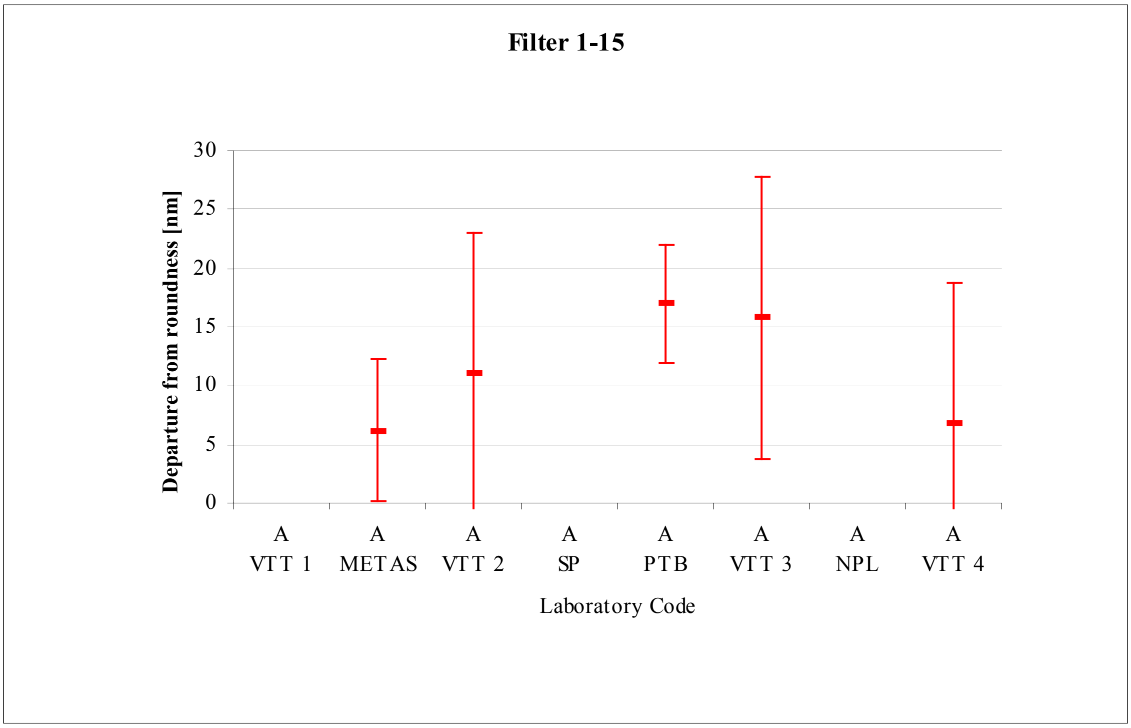


Figure 8. Results for direction A, 1-15 filter.



1 Uncertainty not reported for NPL equal Step method

Julkaisut 1999 - 2001

Tilaukset toimistosihteeri Kirsi Tuomisto, puh. (09) 6167 457,
e-mail kirsi.tuomisto@mikes.fi.

MITTATEKNIIKAN KESKUS
CENTRE FOR METROLOGY AND ACCREDITATION
P.O. Box 239
FIN- 00181 HELSINKI
Tel. +358 9 616 761
Telefax +358 9 616 7467

ISBN 952-5209-60-1
ISSN 1235-5704