A Comparison of Sensitivity Standards in Form Metrology - Final Results of the EURAMET Project 649

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Results of an intercomparison measurement of sensitivity standards are presented. The standards circulated were a flick and two multi-wave standards (MWS). The measurands were form deviation and for the MWS only: Height of the dominant spectral components. For the flick influences from mechanical filtering and calibration are discussed. For the multi-wave standards several influence quantities are identified and discussed. Some of these influence quantities may dominate the result under certain circumstances. It can be shown that standard measurement uncertainties of smaller than 25 nm can be achieved for the amplitude heights of MWS, whereas the form deviation results disagree a little more than expected compared to standard uncertainties of the order of 50 nm.

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NOMENCLATURE

RONt = roundness deviation as defined in ISO 12181
MWS = multi wave standards

1. Background of EURAMET Project 649

Between 2004 and 2005 six European national metrology institutes (NMI), namely PTB (1 = These numbers identify the individual NMIs in the result graphs of this paper), METAS (2), MIKES (3), INRIM (4), and NPL (5) ran the first comparison dealing with multi-wave standards (MWS) [1]. PTB acted as the pilot laboratory and evaluated the form deviations and spectra of the form profiles, from data supplied by the participants. MWS embody superimposed spatial harmonic waves on a cylindrical body. They represent an alternative realization of sensitivity standards used for the dissemination of the length unit to form measurement instruments. Some NMIs already have applied them for analysis of their equipment [6]. The most common sensitivity standards are so-called flick standards or “flicks”, i.e. cylinders with a ground flat. All participants were experienced in calibrating flicks, but only a few of them ever measured multi-wave standards before the project. Therefore it was decided to circulate a flick together with two different multi-wave standards (MWS). The comparison of sensitivity measurement intended to compare and verify the measurement capabilities of participating laboratories and to investigate the effect of systematic influences in the measurement process and ways for their elimination. In case of the MWS it should in particular be examined whether a better stability of the calibrated sensitivity could be achieved.

Although the measurement results were available shortly after the measurements, the results are not yet published. One reason is that the measurements were not completely understood at that time. Recently there has been further progress in the understanding of measurements on multi-wave and flick standards. Therefore, it seemed worthwhile to discuss the measurement results on this new basis.

2. Circulated standards

2.1 Multi-wave standards

Two MWS were circulated, serial numbers MWS-1, and MWS-8. Their profiles contain a superposition of sinusoidal waves with the wave numbers 5, 15, 50, 150, and 500 UPR. MWS-1 is an outer cylinder (Fig. 1), MWS-8 is an inner cylinder (Fig. 2). Both were manufactured at the Fraunhofer Institute for Production Technology (IPT) / WZL of the University of Aachen. Already the form profile of MWS-8 shows that it not only consists of the intended nominal harmonics, but also reveals unexpected additional asymmetry. However, it should be mentioned that it was the first IPT prototype for inner MWS and the achieved quality is not on the same level as the outer standard MWS-1. Recent measurements at PTB of newer inner MWS show a much better manufacturing quality [2].

Since the time of the project the pilot laboratory has enhanced its form measurement capabilities. Therefore new reference measurements were made with a cylinder form measurement machine MarForm MFU110WP in 2011. This machine incorporates a variety of different probe systems, including an optical interferometer [3]. The reference measurements were made with tactile probing elements with radii 0.025 mm (single diamond surface measurement probe), 1 mm, and 3 mm and an optical probe with a spot size of approximately 0.008 mm. No significant difference was found between the form profiles with 0.025 mm probe diameter and the optically acquired ones.

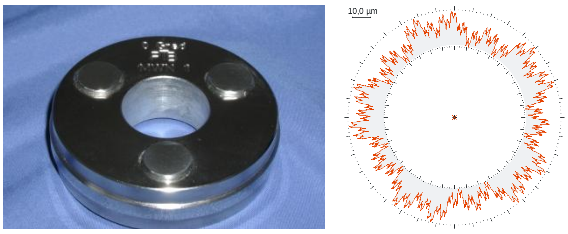

Fig. 1 Photograph and form profile of MWS-1

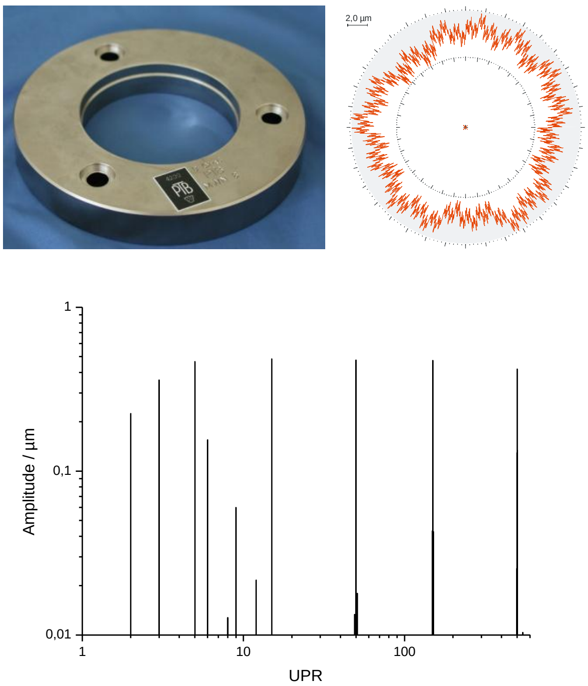

Fig. 2 Top: Photograph and form profile of MWS-8, below: spectrum of MWS-8 form profile (acquired with a 0.025 mm diameter probe)

The reason for the application of different probe radii was to check possible influences from mechanical filtering by the contacting element. Fig. 3 shows a comparison between the spectra of the MWS-1 form profile acquired with a probe diameter of 0.025 mm (for reference) and 3 mm, respectively. Indeed, some small spurious peaks are visible in the 3 mm spectrum, which are not present in the reference spectrum. These can be explained by mechanical filtering i.e. convolution of the probing element geometry and the MWS surface profile during scanning [2]. The critical probe diameter, which is sufficient for full penetration into the valleys of a profile can be calculated after [4]. It is approximately 7 mm for outer contacting of a 500 UPR wave with 1 µm amplitude and an MWS diameter of 80 mm. However, full penetration still can result in profile distortion. This is illustrated in Fig. 4 where an ideal sinusoidal profile is compared with the profile which a probe of critical size would acquire. The sharp corners of the distorted profile translate to new wave numbers in the spectrum. This is the reason why less than half of the critical diameter should be chosen for the probing element when measuring MWS. This would be 3 mm in our case. But as previously shown, even a 3 mm stylus tip diameter results in a distorted spectrum. Morphological dilation may be applied to correct for these effects [2], but were not used throughout the project. Note: For the parameter form deviation RONt the critical size is already small enough.

The number of sampled data points was 9000. However, for the acquisition of the correct spectrum the required number of data points is little more than twice the largest wave number of the MWS . This fact was proven by a comparison of the spectra of the original 9000 points data file and a down sampled version with 1200 points (applied procedure: cubic interpolation). Fig. 5 shows the spectral differences of the original from the down sampled one. Most differences are in a band of ± 20 nm with some additional single peaks at larger, non-dominant wave numbers, which, however, were not further evaluated within the project. This fact is of importance, because some project participants only could acquire a relatively small number of data points.

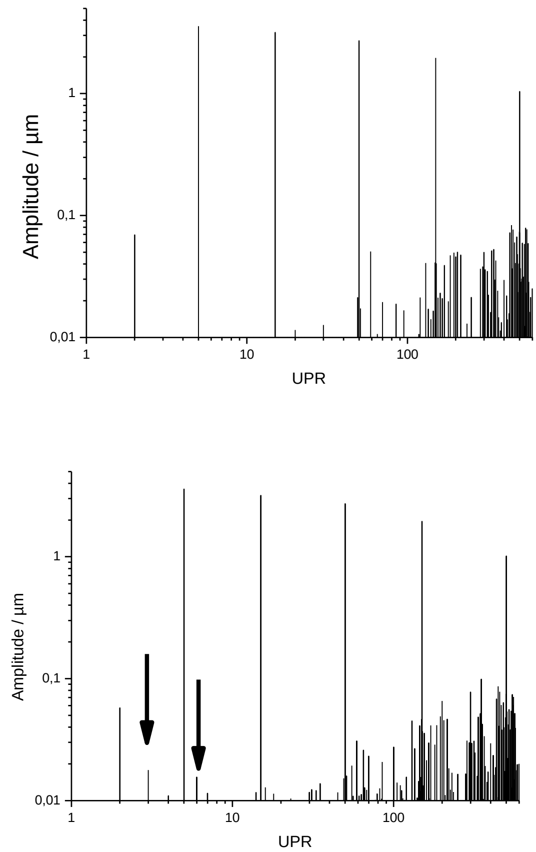

Fig. 3 Spectra of MWS-1 form profiles. Top: probe diameter during acquisition: 0.025 µm; Bottom: probe diameter during acquisition: 3 mm. Spurious peaks are visible (marked with arrows) due to mechanical filtering.

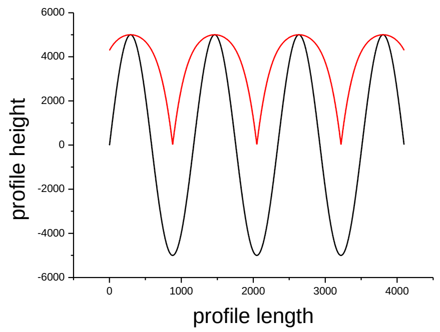

Fig. 4 Comparison of an ideal sinusoidal profile and a distorted profile due to mechanical filtering.

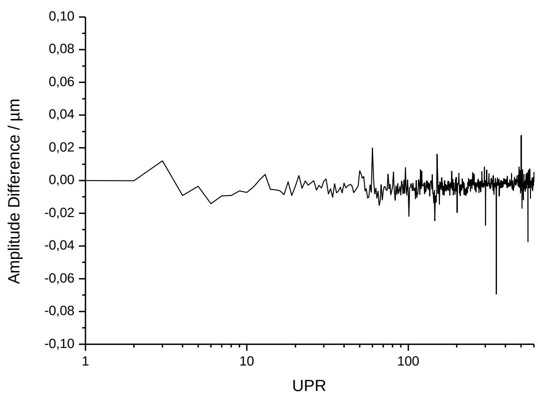

Fig. 5 Spectral amplitude difference between 9000 data points form profile file of MWS-1 and a 1200 points down sampled version.

2.3 Flick standard

Flick standards are widely used in NMIs, accredited laboratories and industry. However, it is well known that their calibration is non-trivial and often results in insufficient measurement uncertainties. Again, mechanical filtering is one of main influence factors [5]. One part of EURAMET project 649 therefore was to clarify the state of the art in flick measurement at the NMI level.

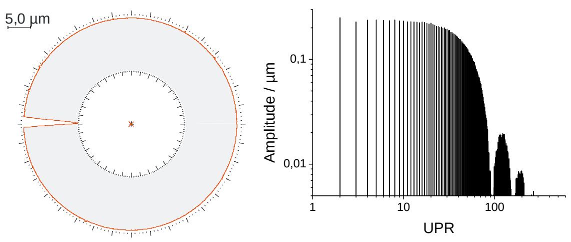

Fig. 6 Form profile and spectrum of the circulated flick

Flicks exist in various sizes and technical realizations. For the project it was decided to use a common 12 µm flick at a 20 mm base cylinder. Fig. 6 shows its form profile and spectrum. The spectrum of flicks is of smaller bandwidth and amplitude height than often assumed. Fig. 6 shows that it decays rapidly, shows zero crossings, and carries no higher amplitude than 0.2 µm. This value should be compared to the amplitude heights of MWS-1, which carries form deviations of the same order of magnitude.

To check the influence of mechanical filtering on flick measurement, the pilot has measured the circulated flick in 2011 with the MFU110WP with 9000 data points by utilizing the three probe diameters 25 µm, 1 mm, and 3 mm. Table 1 shows the results as a function of the filter parameters in absolute values and as differences to the 25 µm reference measurement. Although there is little or no difference for the unfiltered and 500 UPR values, the differences for the 15 UPR values are 0,086 µm and 0,153 µm, respectively.

This result may be unexpected. However, it can be understood quite easily. All probes detect the deepness of the flick with respect to the base cylinder in the same way. However, the convolution of the probe geometry with the sharp flick boundary is very different for the three probes. Therefore these high wave-number components get significantly mechanically filtered in very different ways. Consequently, the Gaussian filter shows different impact in Table 1.

Therefore, it is strongly recommended to only compare flick calibration results that stem from measurements with the same probe diameter. As ISO 12181 recommends a default 1 mm probe diameter, this should be the value of choice [8].

Unfortunately, the probe radius was not fixed for EURAMET project 649. Therefore deviating results were to be expected.

	probe dia.	**Gaussian filtering / UPR**				
		none	**500**	**150**	**50**	**15**
RONt/µm	**25 µm**	11.930	11.875	11.587	9.405	3.874
	1 mm	11.969	11.875	11.574	9.306	3.788
	3 mm	11.982	11.875	11.523	9.092	3.635
diff. to 25 µm	**1 mm**	0.039	0.000	-0.013	-0.099	-0.086
	3 mm	0.013	0.000	-0.051	-0.214	-0.153

Table 1 Roundness deviation RONt of the flick for different probe diameters and filter settings. The lower two lines show the difference to the 25 µm measurement.

3. Measurement results

The participants were free in their selection of the measurement instrument to be used. Most participants selected instruments of the Taylor Hobson Talyrond 73 series, as this device class was utilized by most participants and other NMIs for their roundness reference calibrations. For the calibration of roundness standards like hemispheres, most participants apply error separation procedures like the multi-orientation method. These procedures failed for the artefacts of this project. It is assumed that this is caused by small division errors of the utilized indexing tables and/or angular encoders at the rotating spindle. In addition, multi-orientation methods with constant angular spacing cannot resolve harmonic content with wave numbers that are multiples of the number of orientations [9]. The evaluation of the raw measurement files was performed by each individual participant and additionally by the pilot with the custom-made form profile analysis software "FormCalc", written in IDL [7]. The parameter roundness deviation RONt was evaluated for the reference circle LSCI [8]. The calculation was repeated for the Gaussian filter cut-off wave-numbers 15, 50, 150, 500 UPR, and for no filtering applied.

The spectral analysis of the MWS profiles was performed by the pilot using FormCalc with an embedded FFT algorithm which can deal with any number of data points, not only multiples of 2^n. No filtering was applied to the files. Only the dominant amplitudes 5, 15, 50, 150, and 500 UPR were compared.

All results are displayed with 1 nm resolution, although the measurement uncertainties did not always match such high resolution. The results of PTB (1) stem from the original data of the comparison - not from the measurements in 2011.

3.1 Multi-wave standards – Form deviation RONt

The mean results for the roundness deviation of MWS-1 are summarized in Table 2.

	Gaussian filtering / UPR				
	15	**50**	**150**	**500**	**unfiltered**
RONt/µm	7.179	12.206	15.229	17.377	18.390

Table 2 Roundness deviation RONt of MWS-1 evaluated from the mean value of the participants results.

Fig. 7 shows the absolute deviations of the results from the mean value. Fig. 8 shows the relative deviations of the results for the individual wave numbers. Surprisingly, the unfiltered values agree a little better than the filtered results.

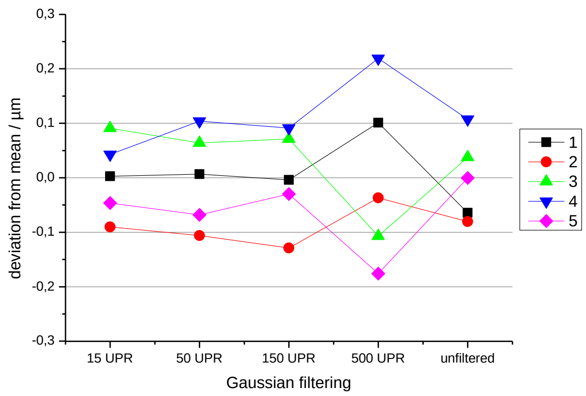

Fig. 7 Absolute deviations of the RONt results of MWS-1 from mean results.

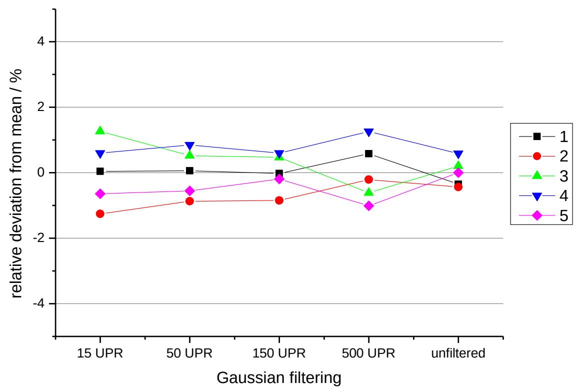

Fig. 8 Relative deviations of the RONt results of MWS-1 from mean results.

Table 3 and Fig. 9 and 10 show the corresponding results for MWS-8.

	Gaussian filtering / UPR				
	15	**50**	**150**	**500**	**unfiltered**
RONt/µm	1.811	2.658	3.308	4.055	4.635

Table 3 Roundness deviation RONt of MWS-8 evaluated from the mean value of the participants results.

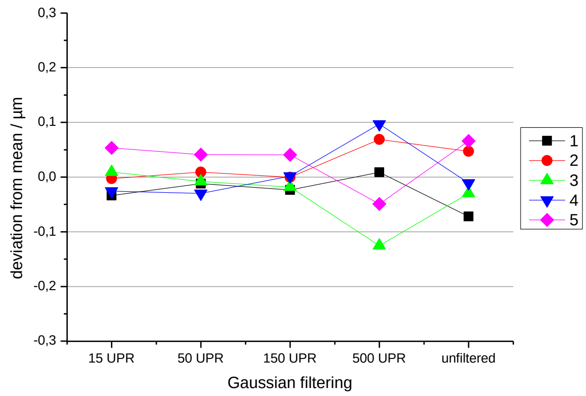

Fig. 9 Absolute deviations of the RONt results of MWS-8 from mean results.

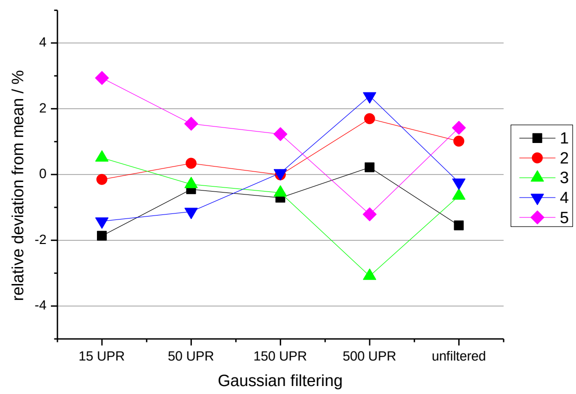

Fig. 10 Relative deviations of the RONt results of MWS-8 from mean results.

3.2 Multi-wave standards – Dominant amplitudes

The mean results for the height of the dominant amplitudes in the spectrum of MWS-1 are summarized in Table 4.

Amplitude height / µm	Spectral wave number / UPR				
	5	**15**	**50**	**150**	**500**
	3.583	3.196	2.725	1.909	0.910

Table 4 Mean results of the amplitude heights of the dominant amplitudes of MWS-1.

Fig. 11 shows the absolute deviations of the results from the mean value, whereas Fig. 12 shows the relative deviation of the results for the individual wave numbers. Surprisingly, the unfiltered values agree a little better than the filtered results.

The agreement is very good, less than 10 nm for the lower wave numbers. Some of the participants only disagree more at the wave number 500 UPR. Although the reason is unknown, it may be supposed that the deviations are caused by non-even data sampling and limited bandwidth of the signal amplifiers.

The relative deviation looks more modulated. However, this is mainly caused by the low absolute deviation of the results, which show up in the denominators of the relative deviations.

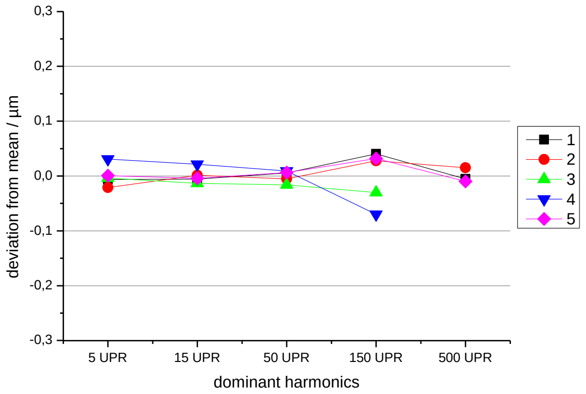

Fig. 11 Absolute deviations of the spectral analysis results of MWS-1 from mean results.

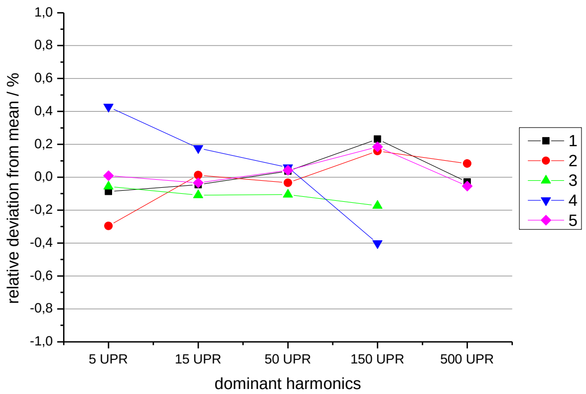

Fig. 12 Relative deviations of the spectral analysis results of MWS-1 from mean results.

Table 5, Fig. 13, and 14 show the corresponding results for MWS-8.

Amplitude height / µm	Spectral wave number / UPR				
	5	**15**	**50**	**150**	**500**
	0.464	0.485	0.480	0.473	0.475

Table 5 Mean results of the amplitude heights of the dominant amplitudes of MWS-8.

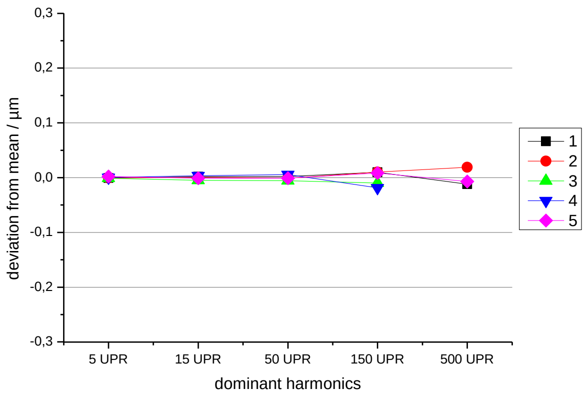

Fig. 13 Absolute deviations of the spectral analysis results of MWS-8 from mean results.

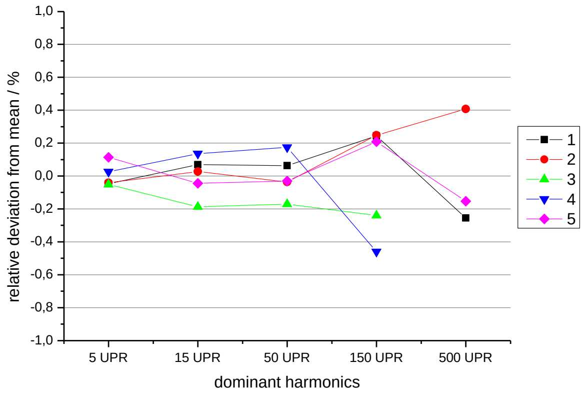

Fig. 14 Relative deviations of the spectral analysis results of MWS-8 from mean results.

3.2 Flick – Form deviation RONt

The mean results of the participants for the roundness deviation of the flick are summarized in Table 6. The individual deviations of the participants are shown in Fig. 15 and 16. The results of participant #2 seem to reveal a wave number (frequency) dependency. This is most probably caused by the large probe diameter (4 mm), as shown in table 1.

	Gaussian filtering / UPR				
	15	**50**	**150**	**500**	**unfiltered**
RONt/µm	3.794	9.295	11.619	11.932	11.964

Table 6 Roundness deviation RONt of the flick evaluated from the mean value of the participants results.

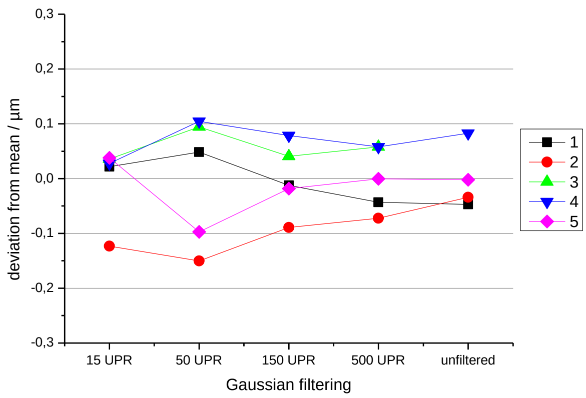

Fig. 15 Absolute deviations of the spectral analysis results of the flick from mean results.

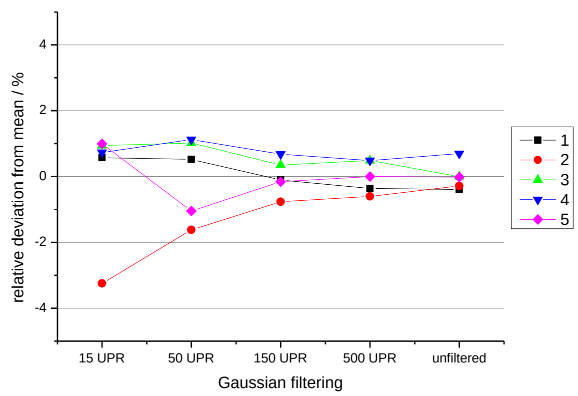

Fig. 16 Relative deviations of the spectral analysis results of the flick from mean results.

4. Some remarks about measurement uncertainty

Most participants claim standard uncertainties below 50 nm for RONt with a RONt dependent term. This seems reasonable at least for smaller roundness deviations. However, the absolute RONt deviations of MWS-1 and the flick seem to lie partly outside this band. The challenge might be a broadband and at the same time large deflection probe calibration. Generally, some participants estimated 0.1% .. 0.25% for this uncertainty contribution. But such small values might only be achievable, if the probe system is calibrated by precise external references like interferometers. Often only flicks or end gauges are used for the calibration of probe systems. However, these methods are sufficient for probes which will only be applied for the low RONt values of hemispheres.

As already mentioned, flick results depend on the diameter of the probe. The variety of the results of the flick can therefore partly be explained by this influence. Another influence might stem from the very different flick data sampling densities of the participants, which varied between 2000 and 4096 data points. It is obvious that the flick boundary shape gets better resolved with higher sampling density.

With the exception of the pilot laboratory no uncertainty claims were made by participants for the spectral analysis. This was to be expected, as only the pilot offered calibration services for these standards at the time of the project. There was no formal uncertainty calculation scheme for the spectral amplitudes of form profiles available. Therefore the project results could serve as an input for future uncertainty estimations.

The pilot laboratory claimed standard uncertainties below 25 nm for the amplitude heights and zero uncertainty for the wave number.

The first value seems reasonable as the low deviations of the spectral values show. However, the data of some participants showed a decreasing agreement with increasing wave number.

The latter claim is a consequence of the closed nature of roundness profiles, where closed sinusoidal waves will show up in the FFT only as integer wave numbers with no uncertainty. This would not be as easy for pseudo harmonics (e.g., for twist analysis of technical shafts) or open profiles.

5. Conclusions

The results showed that the measurement of form profiles of standards with larger roundness deviations is a challenge, even for NMIs. It was shown that spectral analysis of MWS profiles leads to much better agreement and stability than the RONt evaluation. This may be no surprise, because spectral analysis is an integral method, which is based on all data points, where RONt is a measurand which only relies on two data points for the LSCI and four data points for the MZCI reference circles. Furthermore background noise is nearly completely suppressed by the concentration to the dominant amplitudes, whereas noise has a direct influence on the RONt evaluation. Furthermore, it was noticed that the spectral evaluation is less sensitive to small probe calibration errors. The uncertainty calculation of the spectral analysis needs further theoretical input .

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