Metrological Confirmation of the Stylus Profilometer Taylor Hobson Form Talysurf PGI Novus S 10

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T.R. 14/2024 April 2024

I.N.RI.M. TECHNICAL REPORT

Abstract

In the following TR, we validate the new Taylor Hobson Form TalySurf PGI NOVUS S 10 instrument for measuring roughness parameters and step height samples, replacing the previous Taylor Hobson TalyStep I and Talylor Hobson TalySurf Series II instruments. The samples used for comparison include both internal samples, with INRiM calibration certificates issued prior to the instrument change, and the new samples certified by NIST.

Moreover, the difference between the new and old standards for calculating roughness parameters is also investigated, by comparing the results obtained from the same instrument processed with both methods.

Riassunto

Nel seguente studio, validiamo il nuovo strumento Taylor Hobson Form TalySurf PGI NOVUS S 10 per misurare i parametri di rugosità e l'altezza dei campioni a gradini, con lo scopo che quest'ultimo vada a sostituire i precedenti strumenti Taylor Hobson TalyStep I e Taylor Hobson TalySurf Series II. I campioni utilizzati per il confronto includono sia campioni interni, con certificati di calibrazione INRiM emessi prima del cambio strumento, sia i nuovi campioni certificati da NIST.

Inoltre, viene analizzata la differenza tra i nuovi e i vecchi campioni per il calcolo dei parametri di rugosità, confrontando i risultati ottenuti dallo stesso strumento elaborato con entrambi i metodi.

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Introduction

The following Technical Report (TR) is focused on the metrological confirmation of the stylus profilometer. The goal of the calibration is to minimize the measurement uncertainty by enhancing the accuracy of the instrument, while determining the traceability of the measurements.

Calibration is important in establishing the metrological integrity of any measuring instrument. In fact, without proper calibration, inaccuracies may arise, leading to erroneous interpretations of surface profiles and potentially compromising the quality of analyses and processes.

In our study, the calibration of the profilometer was conducted using a piezoelectric device, which is in turn calibrated with a interferometric setup. By using this piezoelectric actuator, step heights are simulated while the profilometer measure a profile, thus providing a known nominal value against which instrument readings could be compared.

This method allows to have a high accuracy and reliability of the stylus profilometer, as it assets for direct validation of measurements outcomes against a reference standard. By varying parameters and observing the response of the piezoelectric device, we obtained some calibration curves, that allow us to correct possible errors or inaccuracies, ensuring traceability to international standards (all this analysis has been carried out by using the international standard ISO 5436).

The objectives of this TR are, firstly, to compare the performance of different stylus profilometers in terms of accuracy and sensitivity and, secondly, to understand the effectiveness of calibration procedures in order to replace the previously used instruments, demonstrating that the current profilometer excels in terms of accuracy, sensitivity, measurement range and speed.

Furthermore, another important role in metrology is played by the surface roughness, which serves as an indicator for understanding the surface quality. In our investigation, we have compared two different recognized standards, ISO 4287 and ISO 21920, to quantify and compare roughness parameters.

This analysis will give some insights into the consistency and agreement of different measurements. The evaluation of profile roughness is based on the acquisition of measurements using the stylus profilometer, and then the application of specific algorithms and filters to extract the final parameters.

In conclusion, this TR is focused mainly on the comparison of different stylus profilometers and their calibration in order to ensure their reliability and accuracy and it is also focused on the analysis of surface roughness comparing two different standards.

1. Taylor Hobson TalyStep profilometer

1.1 Instrument description

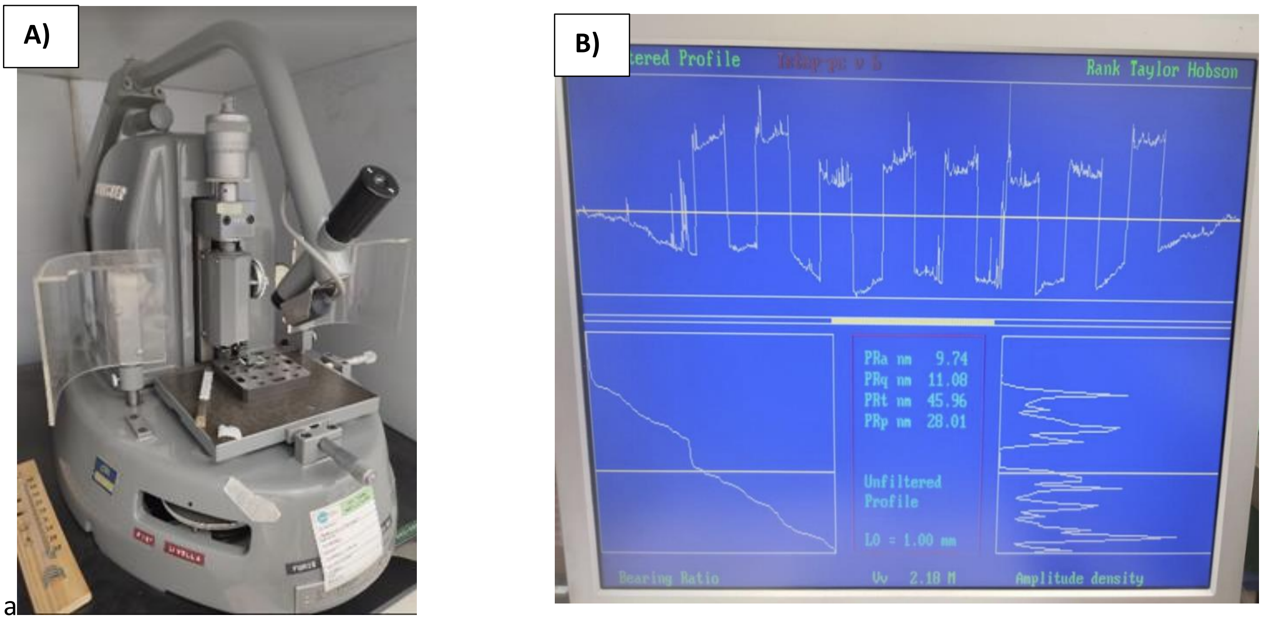


FIGURE 1 – A) TAYLOR HOBSON TALYSTEP INSTRUMENT AND B) SOFTWARE INTERFACE

Taylor Hobson TalyStep (Figure 1 A) provides an electromechanical method for measuring roughness and thin film thickness, measuring surface roughness down to 0.4 nm RMS, using a 0.1 µm probe tip.

The vertical movement of the stylus is detected by an inductance transducer and the electrical signal is amplified.

The stylus can be traversed at three different speeds and the vertical stylus force can be varied (usually is around 1-2 mg).

This stylus profilometer includes [1]:

- A measuring probe with an inductive sensor
- A measuring rod with an electromechanical drive
- An electronic module for regulating the amplification factor of the signal sent from the inductive sensor
- An electromechanical drive
- A device for sending the measuring results to an automatic recorder.

TalyStep profilometer measurements are corrected for a calibration factor, which depends on the calibration with the piezoelectric actuator which in turn has been calibrated interferometrically.

The profilometer permits specification of the signal's amplification factor; the mechanical velocity of the probe (on the rod); and the direction of probe motion. The measuring probe converts the profile height (at a specified point) into an analog signal, which is sent to the control module and then to the automatic recorder (Table 1).

TABLE 1 - TECHNICAL FEATURES OF THE STYLUS PROFILOMETER

Amplification factor	5000; 10000; 20000; 50000; 100000; 200000; 500000; 1000000
Measurement range (nm)	50; 100; 200; 500; 1000; 2000; 5000; 10000
Probe speed (µm/s)	0; 2; 5; 25; 100
Length of probe track, mm 50	Arbitrary (no more than 2)
Range of recording signal	From -10 to +10
Width of recording tape (mm)	50
Vertical increments (nm)	0.005-1.25
Horizontal increments	No more than 16000 points

1.2 Uncertainty budget for step-height

In Table 2 the uncertainty budget for the step height h is reported, that follows the equation:

$$h = C \cdot h_{mean} + \delta_{ref} + \delta_n + \delta_{pl} + \delta_f - h_{mean} \cdot \alpha_a \cdot \Delta t_a$$

Repeatability h_{mean} is assessed within and between series, with 5 profiles taken at evenly distributed sampling sections, including filtering and profile evaluation.

Instrument calibration C involves a calibration factor determined through precision displacement transducer (DPT) calibration, accounting for the uncertainty of the reference gauge.

Additional considerations include (i) profile noise δ_n measured with a flatness standard, and (ii) straightness δ_{ref} verification using a nanometer-size step-height standard.

Elastic deformation uncertainty δ_{pl} is addressed with steps of different materials or finishes, to be estimated individually.

Thermal effects are accounted for the sample thermal coefficient α_a and the local temperature change Δt_a, and local variations are estimated from profiles taken at sampling sections.

Local non-homogeneities δ_f are also included.

INRiM calibration measurement capability (CMC) for step-height measurements performed with this instrument is equal to $U_{95}/nm = Q[1\ nm, 4.6 \cdot 10^{-3}\ h]$, h in nm for step/groove height (ISO 5436-1:2000 type A) with h ranging from 0.01 µm to 15 µm.

TABLE 2 - UNCERTAINTY BUDGET FOR STEP HEIGHT

SOURCE OF UNCERTAINTY	QUANTITY	UNIT	ESTIMATE	STANDARD UNCERTAINTY OF ESTIMATE	UNCERTAINTY TYPE	PDF	DEGREES OF FREEDOM	SENSITIVITY COEFFICIENT	STANDARD UNCERTAINTY OF MEASURAND
	X_i		x_i	$u(x_i)$			v_i	$c_i = \partial f / \partial x_i$	$u_i(h)$/nm
Repeatability	h_{mean}	nm	960	0.6	A	N	15	C	0.6
Instrument calibration	C	-	1	$2 \cdot 10^{-3}$	A	N	100	h_{mean}	1.9
Probe readings	h_{mean} δ_n	nm nm	0	0.1 0.3	A	R N	100 50	1	0.0 0.3
straightness (x-axis)	δ_{ref}	nm	0	1.0	A	R	50	1	0.6
Elastic deformation	δ_{pl}	nm	0	0.0	A	R	50	1	0.0
Thermal effects	α_a Δt_a	K^{-1} mK	0	$1.3 \cdot 10^{-5}$ 500.0	A	R R	50 50	$\Delta t_a \cdot h_{mean}$ 1	0.0 0.0
Local variations non homogeneities	δ_f	nm	0	1.6	A	R	9	1	0.9
Combined standard uncertainty								**u / nm**	**2.3**
Welch–Satterthwaite coefficient								v_{eff}	**130**
Coverage factor								**K**	**2.0**
Expanded uncertainty								**U /nm**	**4.6**

2. Taylor Hobson TalySurf Series II stylus profilometer

2.1 Instrument description

FIGURE 2 - TAYLOR HOBSON TALYSURF SERIES II STYLUS PROFILOMETER

The stylus profilometer Taylor Hobson TalySurf Series II (Figure 2) has a 2 µm nominal radius tungsten tip. The Z-movement is read by an interferometer head, while the form/waviness/roughness of the specimen is sampled. In the meanwhile, 3D profiling is achieved by moving the sample along the y-axis.

The stylus tip is always in contact with the surface and creates a 2D profile at a given scan line.

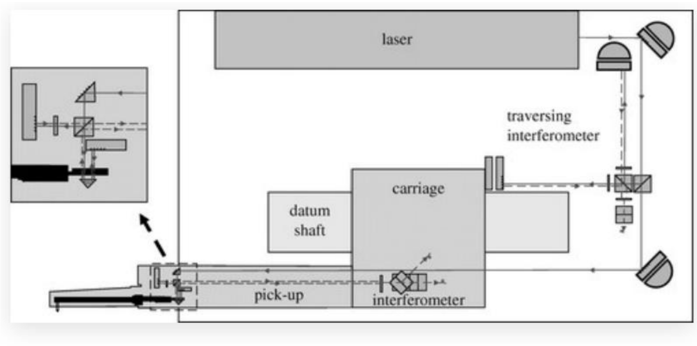


Figure 11 The interferometric transducer of the Form Talysurf.

FIGURE 3 - THE INTERFEROMETRIC TRANSDUCER OF THE FORM TALYSURF.

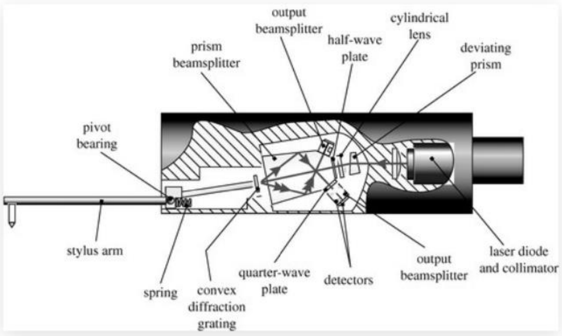


Figure 12 Schematic of the phase grating interferometer transducer.

FIGURE 4 - SCHEMATIC OF THE PHASE GRATING INTERFEROMETER TRANSDUCER.

Figure 3 is a representation of the Form TalySurf interferometric transducer. It was independently developed by Taylor Hobson in the UK and Jiang in China. This revolutionary transducer, along with enhanced calibration techniques, corrected for the non-linearities in measurements due to the arcuate movement of the stylus arm (as it happens in TalyStep).

The transducer featured a linear grating in the horizontal traverse direction to ensure accurate positioning, and mathematical optimization algorithms were provided to determine calibration constants automatically. This allowed for the creation of an accurate Cartesian coordinate system in the measurement plane, enabling precision profile measurement in various application areas. The development of this transducer has enabled surface texture instruments to have a range of 24 mm with a simultaneous resolution of 0.1 nm (Figure 4). This advancement has facilitated precision profile measurement by a single instrument in various application areas [[2]].

The stylus instrument is calibrated at INRiM by using a precision ceramic ball, which in turn is calibrated by an interferometric setup. As recommended by the manufacturer, the stylus pick-up traverses the top profile of a spherical cap of the precision ball to determine the z-sensitivity and Pt parameter, that is the total height of the primary profile. The lower the Pt value, the better the geometry of the tip apex. The lateral scale of the instrument is calibrated by a precision photomask with parallel chromium lines forming a periodical structure up to tens of millimeter size.

The Taylor Hobson Talysurf delivers exceptional precision in measurements. With x-axis accuracy below 1 µm and y-axis accuracy at 1 µm, it ensures reliable results. The z-axis achieves an outstanding accuracy of 1 nm, thanks to a tungsten probe calibrated with a ceramic sphere and verified through interferometric calibration. Capable of measuring profiles up to tens of millimeters with a maximum Z-axis excursion of 1 cm, it covers a wide range of parameters, including Rz and Ra values from 0.01 µm to 20 µm, and RSm values from 50 µm to 500 µm. However, it's important to note that measurements of RSm and step samples fall outside the instrument's measurement range assurance (MRA).

The pros of using this instrument are the high Z-resolution (0.1 nm), the long scan length (several cm), the fast data acquisition for 2D profiles, the excellent repeatability and the fact that the instrument is relatively inexpensive, while the cons are the fact that is a contact method which may lead to some damage of the specimen, 3D measurements are usually slow and moreover it may not analyze perfectly very small details that are present on the surface.

2.2 Uncertainty budget for roughness parameters

Table 3 details the uncertainty budget for the parameters *R*a and *R*q. It is important to note that the other roughness parameters (*R*Sm, *R*p, *R*v, *R*t) are affected by the same error sources, which similarly contribute to their measurement uncertainty.

Consider the following formula for calculating the uncertainty in dimensional measurements, where R represents the total uncertainty, C is the calibration uncertainty, $\delta_{ref},\ \delta_{n},$ and δ_{pl} are the uncertainties due to reference dimensions, nominal measurements, and flatenss respectively, while δ_f is the uncertainty due to force application, and $R_{mean}\cdot\alpha_a\cdot\Delta t_a$ account for thermal expansion.

$$R = C\cdot R_{mean} + \delta_{ref} + \delta_n + \delta_{pl} + \delta_f - R_{mean}\cdot\alpha_a\cdot\Delta t_a$$

TABLE 3 - UNCERTAINTY FOR ROUGHNESS PARAMETERS

SOURCE OF UNCERTAINTY	QUANTITY	UNIT	ESTIMATE	STANDARD UNCERTAINTY OF ESTIMATE	UNCERTAINTY TYPE	PDF	DEGREES OF FREEDOM	SENSITIVITY COEFFICIENT	STANDARD UNCERTAINTY OF MEASURAND
	X_i		x_i	$u(x_i)$			v_i	$c_i = \partial f / \partial x_i$	$u_i(h)$/nm
Repeatability	Ra_{mean}	nm	1000	3	A	N	11	C	3
Instrument calibration	C		1	$5 \cdot 10^{-3}$	A	N	50	Ra_{mean}	0.2
Probe readings	δ_n	nm	0	3	A	N	50	1	1.7
Straightness (x-axis)	δ_{ref}	nm	0	5	A	R	50	1	2.9
Elastic deformation	δ_{pl}	nm	0	2	A	R	50	1	1.2
Thermal effects	α_a Δt_a	K^{-1} K	0	$1 \cdot 10^{-6}$ 1	A	R R	50 50	$\Delta t_a \cdot h_{mean}$ 1	$3 \cdot 10^{-6}$
							Combined standard uncertainty	**u / nm**	**5.5**
							Welch–Satterthwaite coefficient	**v_{eff}**	**90**
							Coverage factor	**K**	**2.00**
							Expanded uncertainty	**U /nm**	**11.0**

The repeatability R_{mean} is assessed within and between series, with 5 profiles for each of the 12 unevenly distributed sampling sections including filtering and profile evaluation.

The instrument calibration C takes into account the calibration done with a sphere of nominal radius 22 mm, and includes the uncertainty of the reference standard (ball gauge).

The probe readings δ_n are determined with a flatness standard, while the straightness (x-axis) δ_{ref} is verified with an optical flat uncertainty of the levelling fitting coefficient.

The elastic deformation δ_{pl} is the uncertainty due to local surface defects/non homogeneities.

The thermal effects are due to local surface defects/non homogeneities.

3. Taylor Hobson Form TalySurf PGI Novus S 10 stylus profilometer

3.1 Instrument description

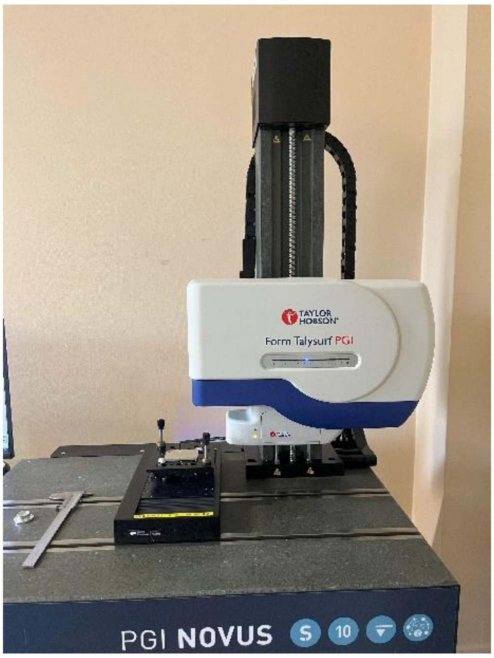


FIGURE 5 - TAYLOR HOBSON FORM TALYSURF PGI NOVUS S10

The Taylor Hobson Form TalySurf PGI NOVUS S 10 (Figure 5) is the most advanced system for angle measurement, surface finish, contour, 3D and diameter measurement by Taylor Hobson.

It is an instrument used for step height measurement (from 5 nm to 800 µm) and micro-surface texture analysis, with high resolution (down to 0.2 nm) and repeatability (ensured by high electronic stability, anti-vibration table and precise stylus control). Moreover, this instrument can also be used for the measurement of thin film by traversing a conical stylus tip across a test groove formed in a deposit or over the edge of the deposit itself. In addition, the high precision of this stylus profilometer allows the measurement of surface characteristics of different devices. Other technical specifications are reported in Table 4.

New Form Talysurf PGI Novus is the dedicated to high precision measurement system for High Precision manufacturers with unparalleled measurement capability. Fully equipped system for complete automation, versatile operation and rapid measurement. The ability to measure surface finish, form, radius and contour with single trace simultaneously has becomes increasingly important for bearing applications & components. This ensure that each element is evaluated as it should be, in relation to the other elements and how they work together.

Measurement accuracy and repeatability performance is directly related to a stable platform. This provide low noise and near flawless mechanical execution of the measuring axes.

The pros of using this instrument are in particular the automated force control, the automatic lift-lower, the diameter and angle capability, the resolution which is down to 0.2 nm and the gauge range up to 20 mm.

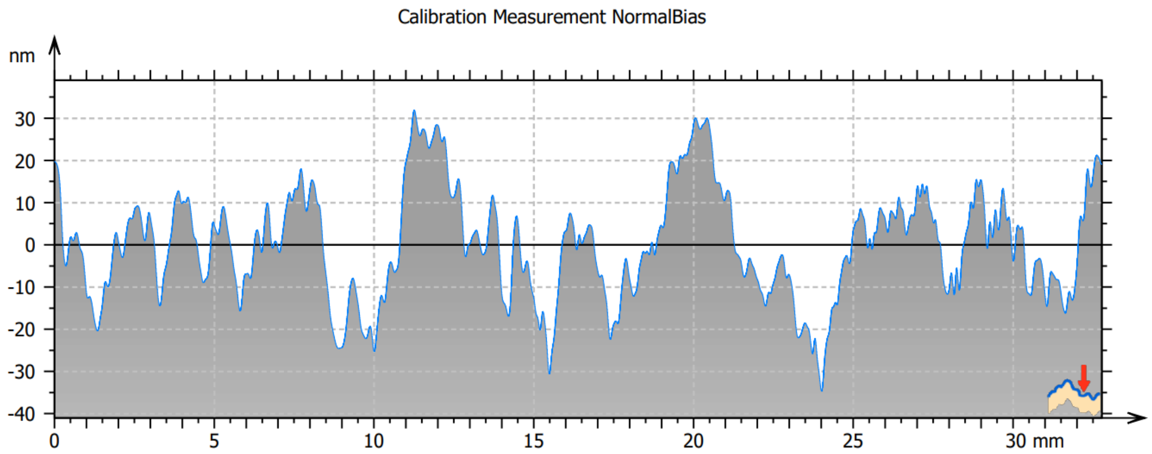
TABLE 4 - TECHNICAL FEATURES OF TAYLOR HOBSON FORM TALYSURF PGI NOVUS S 10

Form uncertainty (Pt)	< 0.15 µm
System noise	Rq < 2 nm, Rz < 10 nm
Nominal measuring range (Z)	10 mm
Resolution (Z)	0.2 nm
Range to resolution	50000000:1
X maximum	120 mm/0.1 mm or 200 mm/0.1 mm
Straigthness uncertainty	transversal unit from 120 mm - 0.08 µm/ transversal unit from 200 mm - 0.110 µm
Measurement direction	Mono/Bi-directional
Uncertainty of Z measurement distance	(1.0 + L [mm]/150)µm
Stylus arm length	Standard length of 100 mm
Tip dimension	Conispheric diamond with radius from 60° 2 µm
Force (checked by software)	30 mgf – 225 mgf

3.2 Calibration of the instrument

The stylus instrument is calibrated at INRiM by using a precision ceramic ball, which in turn is calibrated by an interferometric setup. As recommended by the manufacturer, the stylus pick-up traverses the top profile of a spherical cap of the precision ball to determine the z-sensitivity and Pt parameter, that is the total height of the primary profile, equal to 66.6 nm.

(A)



(B)

ISO 4287 - Primary profile		
F: Form removed (TLSCI, R=22.4496 mm)		
S-filter (λs): Gaussian, 250 µm		
Amplitude parameters - Primary profile		
Pt	66.6010	nm

FIGURE 6 – (A) PRECISION CERAMIC SPHERE CALIBRATED AT INRiM AND (B) ITS PROFILE AND Pt

3.3 Metrological confirmation of the instrument

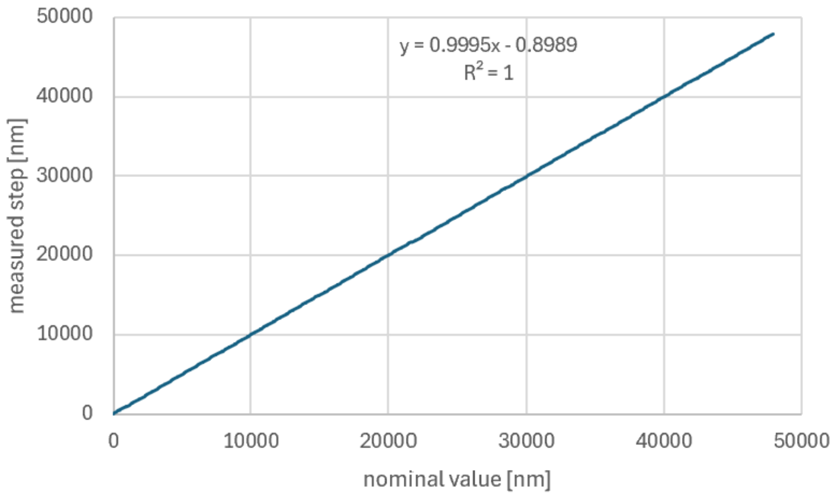
The metrological confirmation process of the stylus profilometer is done through the use with a piezoelectric device.

The piezoelectric device, known for its precise control over mechanical movements in response to electric impulses, was employed to generate controlled displacements.

It operates within a 50 µm working range, controlled via capacitive displacement sensing with settings adjusted through commands sent via an Ethernet interface.

The piezoelectric device has been previously calibrated with an interferometric setup with a He-Ne laser source, which wavelength is calibrated against the INRiM MeP meter. Positioned on a tip/tilt support, the piezoelectric transducer ensures movements parallel the optical axis of a heterodyne interferometer, while displacements are regulated in steps multiple of a quarter of the wavelength of the laser source used in the interferometer through the communication interface of the control electronics.

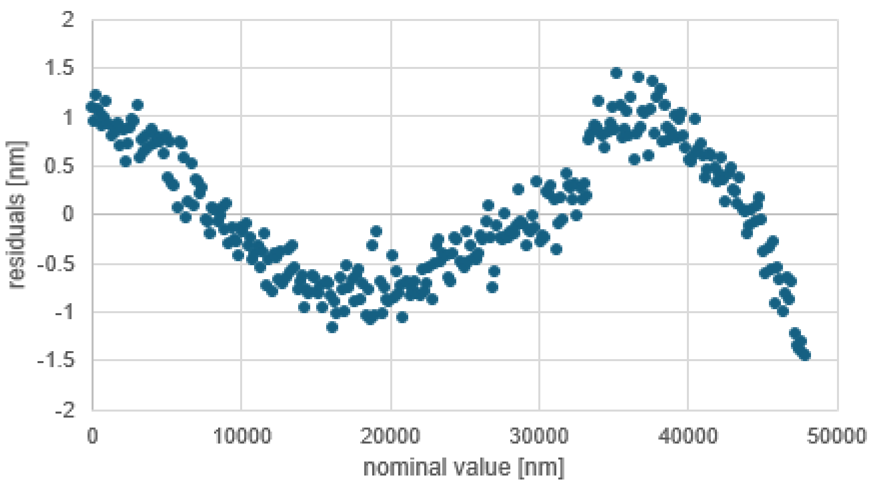
In FIGURE 7 a plot showing the results of the calibration process can be found, and the results comes from INRIiM calibration certificate N° 21-0797-01.



(A)

(B) linear regression equation $y = mx + q$

m	0.99953	-0.8989	q
standard deviation m	2.8E-06	0.07729	standard deviation q
R^2	1	0.67924	uncertainty of the estimation
statistic test F	1.3E+11	303	degrees of freedom of residuals
quadratic sum (SQ) of the regression	5.9E+10	139.793	SQ residuals
	variance		



(C)

FIGURE 7 – (A) CALIBRATION OF THE PIEZOELECTRIC DEVICE WITH THE INTERFEROMETRIC SETUP (B) LINEAR REGRESSION EQUATION AND (C) RESIDUALS OF THE LINEAR FIT

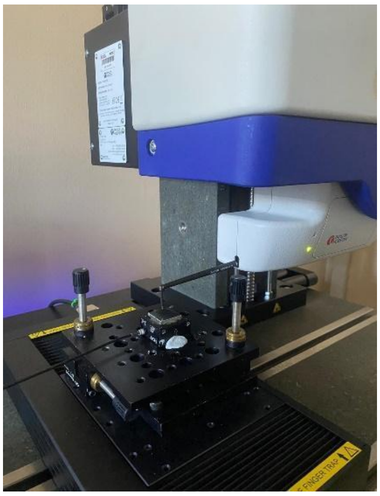


FIGURE 8 - PIEZOELECTRIC DEVICE USED DURING THE CALIBRATION PROCESS OF THE STYLUS PROFILOMETER

For calibrating the stylus profilometer (Figure 8), electric impulses of varying magnitudes were applied to the piezoelectric device, resulting in corresponding movements of known distances simulating step heights. These movements were measured by the stylus profilometer, which recorded the displacement of the stylus tip with nanometer precision.
To ensure accuracy, each step of the calibration process was rigorously executed.
Additionally, calibration procedures were repeated multiple times to assess repeatability and consistency.

Moreover, graphical representations of the responses obtained from both the piezoelectric device and the stylus profilometer were analyzed to validate the calibration process. These plots illustrate the relationship between the applied input signal from the piezo (Figure 9) and the corresponding output signal given by the profilometer (Figure 10), ensuring a good correlation between the movement of the stylus and the electric impulse generated by the piezoelectric.

Figure 9 is a profile with 8000 points, while Figure 10 is a measurement from the stylus profilometer with 10000 points with a speed of 1.5 mm·s^{-1}.

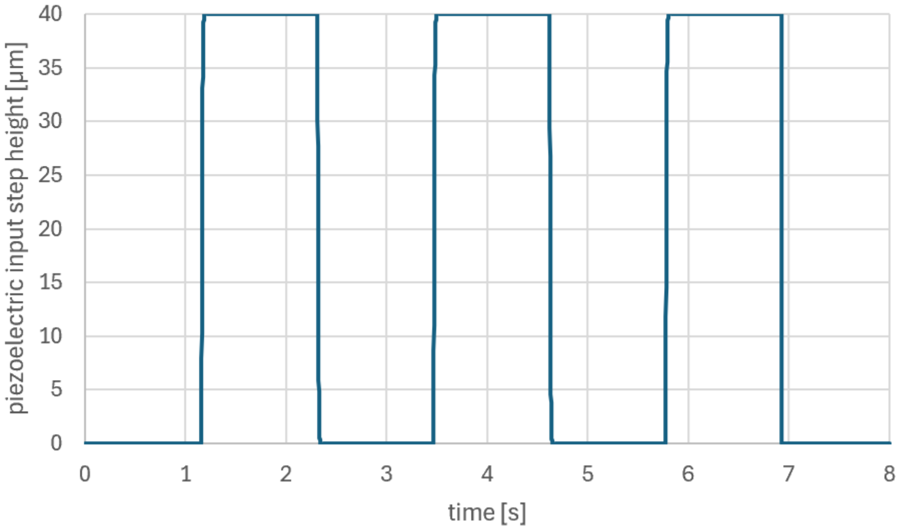


FIGURE 9 - SIGNAL FROM PIEZOELECTRIC SIMULATING STEP HEIGHTS

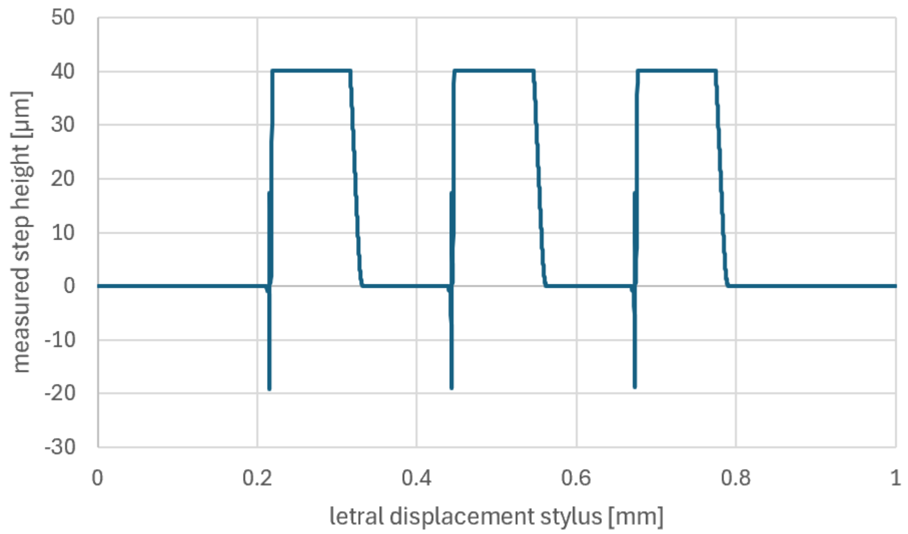
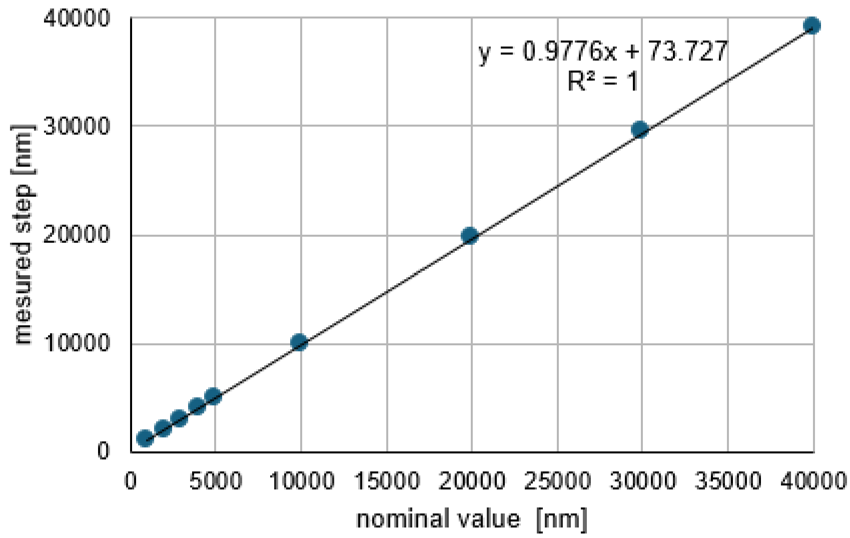


FIGURE 10 - SIGNAL MEASURED BY THE STYLUS PROFILOMETER

As shown in Figure 9 and in Figure 10 a high similarity between the responses are observed, affirming the consistency and reliability of the new stylus profilometer.

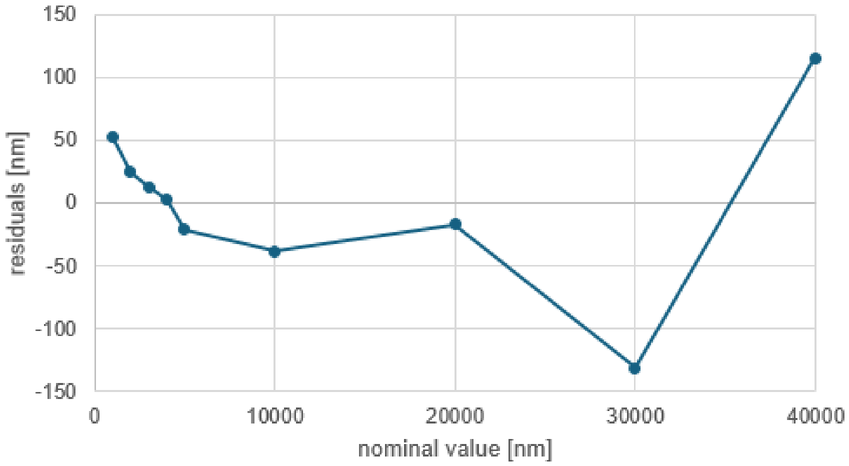
In conclusion, the analysis reveals a good accuracy of the instrument even if the bump, which is shown before the actual step, will need further investigations.



(A)

(B) linear regression equation $y = mx + q$

m	1.0	73.7	q
standard deviation m	0.0	33.3	standard deviation q
R^2	1.0	72.0	uncertainty of the estimation
statistic test F	292739.2	7.0	degrees of freedom of residuals
quadratic sum (SQ) of the regression	1515454730.0	36237.7	SQ residuals
	variance		



(C)

FIGURE 11 – (A) CALIBRATION OF TAYLOR HOBSON FORM TALYSURF PGI NOVUS 10 S 10 (MEASURED STEP ON Y AXIS) BY USING PIEZOELECTRIC DEVICE (NOMINAL VALUES ON X AXIS), (B) LINEAR REGRESSION EQUATION AND (C) RESIDUALS OF THE LINEAR FIT .

From Figure 11 we can see that the coefficient of the interpolated line is equal to 1.006, and insures a good linearity since the R^2 is equal to 1.

Table 5 summarizes the measurements obtained during the calibration process, with step height from 50 nm to 40 µm.

Table 5 - RESULTS OF THE CALIBRATION OF THE STYLUS PROFILOMETER

Nominal step height	Piezoelectric error	Measured step height	Error CMC	E_n
nm	nm	nm	nm	
50	0.7	50.7	1	-0.6
100	0.7	100.5	1.1	-0.4
250	0.7	250.3	1.5	-0.2
500	0.7	499.4	2.6	0.2
750	0.8	750.2	3.7	-0.1
1000	0.9	1001.9	4.8	-0.4
2000	1.3	2001.5	9.5	-0.2
3000	1.7	2999	14.1	0.1
4000	2.1	4003.5	18.8	-0.2
5000	2.6	5006.9	23.6	-0.3
10000	5	10012.8	47.1	-0.3
20000	10	20020	94.1	-0.2
30000	15	30025.2	141.1	-0.2
40000	20	40016.8	188.1	-0.1

The definition of criteria for evaluating the compatibility or difference between two measurements in metrology is crucial and should be based on a clear understanding of the measurement uncertainties as well as the specific requirements of the application area.

The index of compatibility between two measures E_n can be expressed as follows:

$$E_n = \frac{M_1 - M_2}{\sqrt{{U_{M_1}}^2 + {U_{M_2}}^2}}$$

With M_1 and M_2, measured values and U_{M_1} and U_{M_2} the expanded uncertainties associated with it.

The compatibility judgment is defined as follows:

- **Compatible or Identical:** If the index is close to 0, it indicates that the differences between the two measures can be attributed to the measurement uncertainties, and thus, the measurements are considered compatible or identical within their uncertainties.
- **Significant Difference:** If the index deviates significantly from 0, it suggests that the differences between the measurements cannot be explained solely by a statistical dispersion, thus indicating a significant difference between the two measures.

Two difference thresholds are defined:

- **Non-Significant threshold**: An index between -1 and 1 may indicate that the measurements are statistically indistinguishable in the context of their uncertainties. The exact values of these thresholds may vary depending on domain-specific conventions or accuracy requirements.
- **Significant Threshold:** An index above these thresholds (less than -1 or greater than 1) can be interpreted as indicating a significant difference and should investigated.

The E_n coefficient, used to assess results compatibility, indicates that the majority of measurements fall within acceptable limits (E_n < 1), reaffirming the overall reliability of the metrological confirmation.

The metrological confirmation results reveal a high degree of accuracy for most piezoelectric steps, as evidenced by the minimal discrepancy between the measured and nominal values.
In addition, the set of data obtained from the measurements has been put into a plot in order to find the interpolation line and to have a comparison with the one obtained and certified with the previous instrument.

In conclusion, the calibration process yielded interpolation lines for both the calibration data and the certified values. While there were slight differences between the two sets of data, it is important to note that these differences were relatively small. The interpolation line derived from our calibration data exhibited a slight tendency to overestimate measured steps and a systematic bias towards higher values compared to the interpolation line from certified values. However, these discrepancies were minimal, indicating a high level of agreement between the two sets of data.

The comparison reaffirmed the effectiveness of the calibration process using the piezoelectric device in ensuring the accuracy and reliability of the new instrument. Despite minor discrepancies, the new instrument demonstrated a high level of agreement with the measurements obtained from the old instrument, validating its suitability for replacing the previous one.

Therefore, based on the comparison results, it can be concluded that the new instrument calibrated using the piezoelectric device is capable of providing accurate and reliable measurements consistent with those obtained from the old instrument. This further supports the decision to replace the previous instrument with the new calibrated one.

4. Comparison of data between old and new instruments

4.1 Roughness measurement

A comparative study was carried out on the roughness measurement, by comparing the results obtained by Taylor Hobson TalySurf Series II (old instrument) with that ones obtained with Taylor Hobson Form TalySurf PGI NOVUS S 10 (new instrument).
Two specimens had been compared according to EN ISO 4287:2009.

- 521X: sine roughness specimen (type C1)
- 526X: sine roughness specimen (type C1)

The results of the comparative study for each specimen are presented below.

TABLE 6 - COMPARISON OF CALIBRATION RESULTS FOR SPECIMEN 521X, ALL THE RESULTS REPORTED IN THE TABLE ARE (MEAN VALUES ± EXPANDED UNCERTAINTY).

Calibration date	2021 old instrument	2024 new instrument	E_n (%)
Ra [µm]	0.39 ± 0.02	0.39 ± 0.02	0.15
Rz [µm]	1.51 ± 0.06	1.48 ± 0.06	0.35
RSm [µm]	15.00 ± 0.22	15.00 ± 0.22	0.01

TABLE 7 - COMPARISON OF CALIBRATION RESULTS FOR SPECIMEN 526X, ALL THE RESULTS REPORTED IN THE TABLE ARE (MEAN VALUES ± EXPANDED UNCERTAINTY).

Calibration date	2021 old instrument	2024 new instrument	E_n (%)
Ra [µm]	3.16 ± 0.11	3.16 ± 0.11	0.02
Rz [µm]	10.01 ± 0.35	10.42 ± 0.37	-0.80
RSm [µm]	99.93 ± 0.68	99.90 ± 0.68	0.03

The results obtained following the comparative study conducted on the two specimens mentioned above, show that the difference of the measurements of the specimen being compared are below the threshold of significant difference, it can then be concluded that the new instrument meets the criteria for its roughness measurement function.

4.2 Step Height measurement

A comparative study was carried out on two Step Height measurement on VLSI samples, which have a certificate from the National Institute of Standards and Technology (NIST). The results are reported in **TABLE 8** and **Table 9**, and shows the capability of the Taylor Hobson Form Talysurf PGI Novus 10 S 10 for measuring steps in a range from tenth of micrometer to tenth of nanometer.

TABLE 8 - RESULTS FOR SPECIMEN 30557, ALL THE RESULTS REPORTED IN THE TABLE ARE (MEAN VALUES ± EXPANDED UNCERTAINTY).

Laboratory	NIST	INRiM	E_n (%)
Mean height [µm]	51.003 ± 0.273	51.139 ± 0.240	-0.35

Table 9 - RESULTS FOR SPECIMEN 12392, ALL THE RESULTS REPORTED IN THE TABLE ARE (MEAN VALUES ± EXPANDED UNCERTAINTY).

Laboratory	NIST	INRiM	E_n (%)
Mean height [nm]	43.6 ± 1.00	43.9 ± 1.00	-0.23

5. Comparison between ISO 4287:2009 and ISO 21920-1:2022 standards

The comparison of results between ISO 4287:2009 and ISO 21920-1:2022 is a crucial step in assessing the performance and accuracy of surface roughness measurement methods. In this section of the technical report, we will take a close look at the differences and similarities between these two standards, highlighting their specifications, methodologies, and implications for measurement results. This comparative analysis will identify any differences, improvements or advantages offered by the new ISO 21920-1:2022 compared to the old one, the ISO 4287:2009.

The new standard changes the way the mechanical profile is defined, using a morphological erosion filter that sharpens peaks and softens valleys, thereby modifying the measured roughness values.

The diameter of the probe (also known as the stylus tip diameter) directly affects how the surface profile is processed by the software morphological filter. A smaller probe radius allows finer details on the surface to be detected, on the contrary a bigger stylus tip can significantly alter the measured roughness results, especially for surfaces with very fine features, as these small peaks would be removed by the filter.

In this study, the specimen studied is a standard with a mean roughness value of Ra=3.15 µm.

Using a morphological filter with an erosion diameter of 2 µm for measurements in compliance with both ISO 4287:2009 and ISO 21920-1:2022, we observed no significant differences (Table 11) in the measured surface roughness parameters. The consistency across the parameters Ra, Rq, Rz, Rsk, Rsku, and RSm suggests that the application of this specific filter does not notably affect the outcome when transitioning from the old to the new standard.

Uncertainties reported in **TABLE 10** and **TABLE 11** are calculated by using INRiM CMC.

TABLE 10 - COMPARISON OF RESULTS FROM THE TWO STANDARDS FOR AVERAGING DIFFERENT PARAMETERS (SP526X). ALL THE RESULTS REPORTED IN THE TABLE ARE (MEAN VALUES ± EXPANDED UNCERTAINTY) OBTAINED WITH A PROBE RADIUS OF 2 µm.

	ISO 4287:2009	ISO 21920:2022	Difference (%)*
Ra [µm]	3.16 ± 0.11	3.16 ± 0.11	0.00
Rq [µm]	3.51 ± 0.12	3.51 ± 0.12	0.00
Rz [µm]	10.00 ± 0.35	10.00 ± 0.35	0.00
Rsk	0.01 ± 0.01	0.01 ± 0.01	0.00
Rsku	1.50 ± 0.05	1.50 ± 0.05	0.00
RSm [µm]	100.00 ± 0.68	100.00 ± 0.68	0.00

***Results provided from the software MountainsMap only with 2 decimal digits**

By applying a morphological filter with erosion diameters of 2 µm and 50 µm using ISO 4287:2009 on 526X sample, we observed significant differences in surface roughness measurements, as shown in **TABLE 11**. The results for the parameters Ra, Rq, Rz, Rsk, Rsku, and RSm suggest that the use of specific filters significantly affects the outcomes.

TABLE 11 - (A) RESULTS FOR DIAMETER OF PROBE 2 µm and (b) RESULTS FOR DIAMETER OF PROBE 50 µm ON THEN SAME STANDARD

	ISO 4287:2009 (a)	ISO 4287:2009 (b)	Difference (%)
Ra [µm]	3.06 ± 0.11	3.16 ± 0.11	0.99
Rq [µm]	3.43 ± 0.12	3.51 ± 0.11	3.27
Rz [µm]	10.10 ± 0.35	10.00 ± 0.35	2.33
Rsk	0.25 ± 0.01	0.00 ± 0.01	100.00
Rsku	1.60 ± 0.06	0.00 ± 0.01	100.00
RSm [µm]	100 ± 0.68	100 ± 0.68	0.00

In conclusion, our comparative study between ISO 4287:2009 and ISO 21920-1:2022 revealed remarkable similarities in the measurement results of surface roughness parameters.

However, the introduction of an erosive morphological filter in the new standard has led to changes in the way the mechanical profile is defined, thus impacting the measured roughness values.

- Filtered (Erosion, Diameter: 2 µm, Figure 12 (a)):

  This filter applies an erosion algorithm with a very small diameter of 2 micrometers. This is likely to have a minimal impact, removing only the finest details from the surface profile. Such a fine erosion filter might be used to eliminate the smallest irregularities that could be considered noise rather than a part of the surface texture being measured.

- Filtered (Erosion, Diameter: 50 µm, Figure 12 (b):

  The second filter has a significantly larger erosion diameter of 50 micrometers. This filter would smooth out more significant features of the surface profile, potentially altering the measured values of roughness parameters more substantially.

(a)

(b)

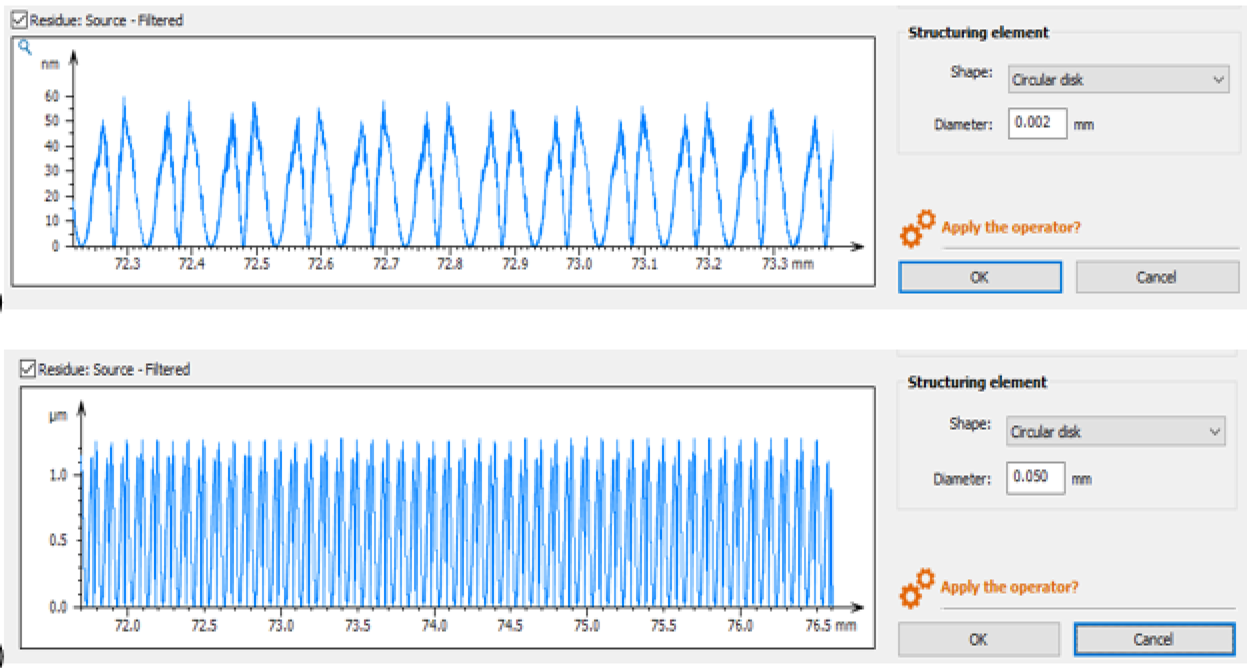


Figure 12 - RESIDUES OF THE MORPHOLOGICAL FILTRATION ON 526X SAMPLE WITH PROBE DIAMETER OF 2 µm or 50 µm

Furthermore, it is crucial to acknowledge that the specific nature of the specimen under study also plays a significant role in the surface roughness measurement results. For instance, materials with more complex surface structures or particular irregularities may react differently to measurement parameters and the specific methodologies outlined in standards. Similarly, variations in surface texture, such as the presence of pits, bumps, or defects, can affect how the probe interacts with the surface and bias the measurement results. Therefore, to obtain accurate and meaningful assessments of surface roughness, it is imperative to consider both the applicable standards and the intrinsic characteristics of the specimen under study, thereby ensuring a robust and reliable interpretation of the measured data.

6. Conclusion

We verified the correct functioning of the new instrument which can replace both the previous ones.

The measured values are in accordance with the previous calibration certificates with a maximum error of compatibility $E_n < 0.8$.

ISO 21920:2022, includes the application of a morphological filter to the profile, the structuring element is a disk of radius equal to the stylus tip used to measure the profile itself.

The comparison between the old ISO 4287:2009 and new ISO 21920:2022 standards showed that, for samples with a mean spacing between the features greater than stylus tip radius, the new processing method does not affect the results.

References

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