FINAL PUBLISHABLE REPORT

Grant Agreement number	18RPT01
Project short name	ProbeTrace
Project full title	Traceability for contact probe and stylus instrument measurements

Project start date and duration:		01 September 2019, 48 months
Coordinator: Murat Aksulu, TUBITAK Tel: +90 (262) 679 50 00 E-mail: murat.aksulu@tubitak.gov.tr Project website address: http://probetrace.org		
Internal Funded Partners: 1. TUBITAK, Turkiye 2. BIM, Bulgaria 3. CEM, Spain 4. DMDM, Serbia 5. FSB, Croatia 6. GUM, Poland 7. INRIM, Italy 8. IPQ, Portugal	External Funded Partners: 9. NIS, Egypt	Unfunded Partners: 10. SASO-NMCC, Saudi Arabia
RMG1: ME, Montenegro (Employing organisation); FSB, Croatia (Guestworking organisation) (RMG contract terminated before the start)		

TABLE OF CONTENTS

1 Overview

The overall aim of this project was to develop traceable and cost-effective measurement capabilities for the calibration of form and surface roughness standards. Surface texture and form of products are important features to be examined and numerically characterised as parameters for engineering and scientific purposes. Such features of surfaces have great impacts on wear resistance, bearing, sliding and lubricating properties, fatigue and corrosion resistance, functionality, etc. Form and surface measurement devices with contact probes and stylus are used to characterise such surfaces. This project improved the scientific knowledge, instruments, methods and research capability in metrology for contact measurement probes and stylus instruments and enabled calibration labs to develop new capabilities for self-provision of traceability to the SI unit of length, the metre. Calibrations of reference stylus instruments using novel displacement generators (DG) were performed with expended uncertainties between 1 - 70 nm in all calibration setups except one. Two novel algorithms and dedicated open source software were developed for calibration of stylus devices using sphere standards. The software allowed calibration of not only the devices of certain manufacturers, but of all roughness measurement devices using spheres. Calibrations of form measurement device's probes using novel DG were performed with expanded uncertainties between 10 - 200 nm in all calibration setups. Calibration of the DGs using state of the art set ups realised by laser interferometers was performed to obtain direct metrological traceability to SI metre with the uncertainties of 5 nm and experimental investigations of DGs using precise angular measurement systems. A VBasic software for random noise reduction in surface roughness and form profiles, and a Python software for random noise reduction in roundness profiles were developed. Measurement profiles with random noise obtained from roughness and form measurement devices in calibration laboratories can be cleared of noise, and uncertainty of the measurements can be reduced with these softwares.

2 Need

Surface texture is of great importance in specifying the function of a surface. A significant proportion of component failure starts at the surface due to either an isolated manufacturing discontinuity or gradual deterioration of the surface quality influencing the proper functioning of the products. Therefore, in the manufacturing industry, surface properties need the periodical check to be within certain predetermined tolerances of roughness and form. The surfaces outside of these limits will result in failures in the performance of the products, influencing the productivity of European manufacturing industries. An accurate measurement of surface roughness and form is vital to quality control of the machining of a workpiece.

Form errors of machined parts are measured in a production line mostly by using coordinate measuring machines (CMMs) which are the key devices for factory of the future (industry 4.0). Reindustrialisation with the demand for higher precision has led to a new generation of CMMs working in scanning mode (which can measure dimension and form simultaneously). Since the contact measurement probes are used in scanning mode with CMMs, the dynamic performance of the probes must be evaluated.

Use of probes for form measurements in scanning mode with a fast scanning speed might be problematic due to required high data acquisition rates, therefore the dynamic performance of the probe including the electronics of the instrument should be well calibrated. For the surface roughness devices, there was a need for new traceable standards due to a recent increase in the required measurement ranges (e.g. 1000 µm).

Although there are documentation and methods for calibration of contact stylus instruments (ISO 12179; ISO 25178-701:2010 and DKD-R 4-2), there was no documentation for alternative routes or detailed investigations for calibration of reference stylus instruments used for calibration of reference standards of secondary level labs.

This project investigated portable traceable displacement generators and their use to establish new direct routes to SI unit metre definition, considering the emerging demands of industry in terms of dynamic properties, precision and larger measurement ranges in regard to contact probes used in form and surface roughness measurements. Knowledge transfer from experienced NMIs to those less experienced was necessary to ensure the development of new cost-effective capabilities that will enable emerging NMIs to achieve direct traceability to the SI unit, the metre.

3 Objectives

The overall goal of this project was to develop traceable and cost-effective measurement capabilities for the calibration of form and surface roughness standards with uncertainties in the range 10 nm –100 nm. The specific objectives of the project were:

1. To calibrate reference stylus instruments for surface roughness measurements using novel portable displacement generators with uncertainties in the range 10 nm–100 nm and to evaluate the efficacy of displacement generators vs existing methods (e.g. depth setting standards) for calibration of stylus devices. Further, to develop novel software for the calibration of stylus devices using sphere standards.
2. To calibrate reference probes for form measurements in static and dynamic mode using novel portable displacement generators with uncertainties in the range 10 nm –100 nm and to evaluate the current state of the art for calibration of flick standards.
3. To investigate the traceable calibration of transducers to be used as portable displacement generators under static (+/-1000 µm) and dynamic (+/-100 µm) measurement conditions, including investigations into the set-up of the generators to be used as 'portable'. Further, to prepare two best practice guides on their use in the calibration of stylus instruments and form measurement probes.
4. To develop noise reduction software, including the use of numerical methods for random noise bias reduction, that can be used to pre-process roughness and form profiles data to reduce the overall uncertainties down to a level of 10 nm in roughness and roundness measurements.
5. For each project partner, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation. In addition, for partners to develop a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies to be discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

4 Results

Displacement generators, electrical devices capable of stable and repeatable displacements up to hundreds of micrometres and nanometric resolution are equipped with a closed loop control system based on capacitive, optical or piezoresistive sensors. When they are calibrated with respect to the wavelength of light with an interferometer, they can provide displacements in the nanometer size range that are traceable to the SI unit of length. These generators may provide static and dynamic displacements for calibration and performance checks of stylus devices and form measuring probes, if sufficiently stable and linear. Various types of these devices were calibrated and used during the project for stylus instruments of surface roughness testers and form measuring probes.

4.1 Calibration of reference stylus instruments using novel portable displacement generators vs existing methods

TUBITAK calibrated the reference stylus instrument using both a displacement generator (DG) and groove depth standards (Figure 1) for the whole range D = 0-1000 µm depth. Using the very precise displacement capability of a DG, a groove depth measurement profile was simulated using the DG vertically (Figure 2). The main advantages of using a DG are that the DG displacement uncertainty is low, and the groove depth standard can be simulated at all depth values needed.

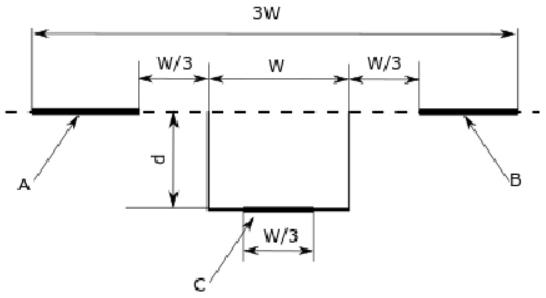


Figure 1. Definition of D parameter for Type A1 (ISO 5436-1)

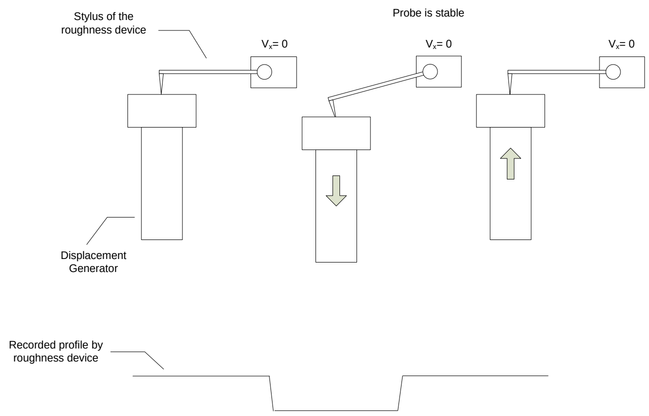


Figure 2. Simulation of groove depth standard calibration using a DG

The uncertainty budgets for the calibration of stylus device using DG were prepared. The max difference between static and dynamic calibration results obtained using DG and the calibration results obtained using groove standard was less than 90 nm for the range 0-1000 µm. These differences were always sufficiently smaller than the calculated uncertainties of differences (Figure 3). Therefore, it can be clearly stated that the calibration of the stylus instrument using DG and the calibration of the stylus instrument using groove depth standard for the whole range 0-1000 µm depth are compatible. The max standard uncertainty for the calibration of the stylus instrument using DG is less than 22 nm for the whole range 0-1000 µm.

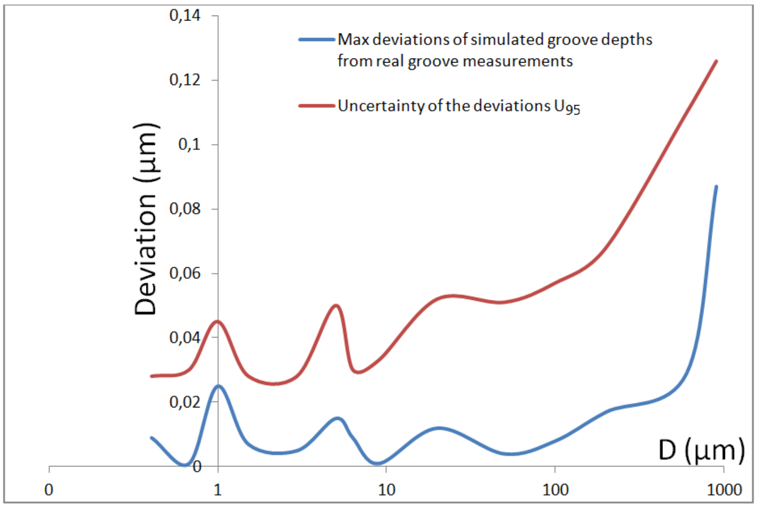


Figure 3. Max deviations of simulated groove depths produced by DG from measured groove depths and the uncertainties of the max deviation

BIM completed the calibration of the reference stylus instrument using DG (Figure 4). The movement of DG measured with stylus instrument was compared with calibrated depth measurement standard, type A1, with nominal value 2,35 µm. The movement of the displacement generator was performed by a LabView software *created* by BIM. The time and distance of movement could be changed by this software which allows different depth values to be simulated. The automatisation of the movement of the DG allows the generated profile to be symmetrical in whole measurement plane.

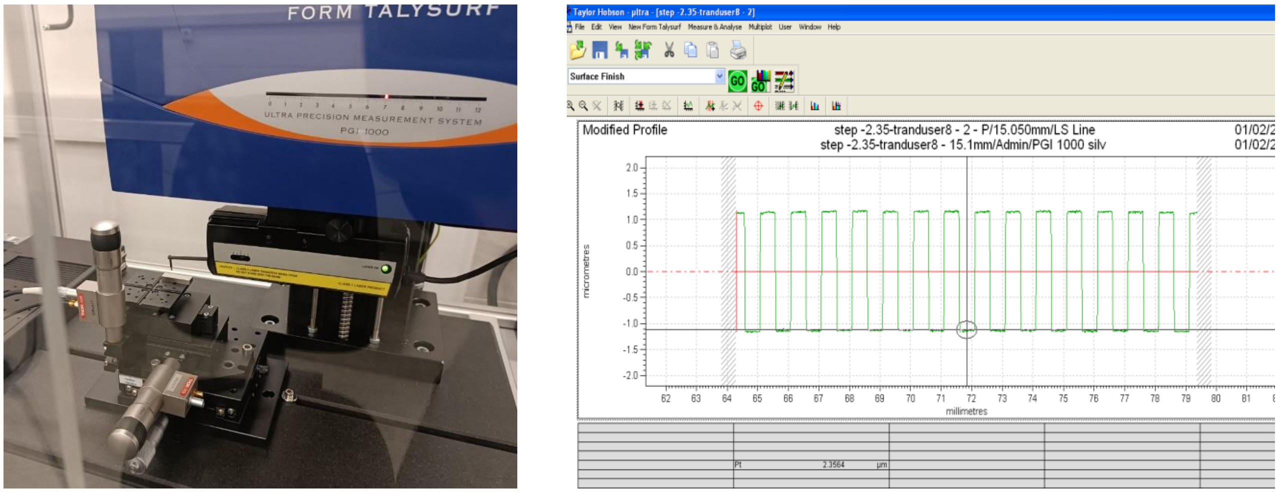


Figure 4. Set up of the displacement generator measured with PGI 1000 and automated simulated profile by DG measured with PGI 1000.

The uncertainty budget for the calibration of stylus device using DG was prepared. The values of standard deviations of measured depth artefact and simulated depth profile by DG are the same (approximately 5 nm) which is due to the fact that the movement of the DG is automated.

DMDM performed calibration with Pi DG in the range up to 50 µm and compared obtained results with calibration using depth setting standard in the range up to 7.894 µm. Steps generated by actuator are the same as steps realised by depth setting standards: 0,062µm 0,236µm 0,35µm 0,925µm 2,61µm 3,794µm 7,894µm. The piezo displacement generator was set under the stylus of the roughness device in vertical position. For precise and proper measurement, a small optical flat was used at the top measuring face of the DG in order that stylus made correct sense of the vertical PG displacement. The movement of the DG is performed by a Pi commercial software PiMikroMove using its Wave Table Editor. Stylus device probe was calibrated using DG in static and dynamic mode. The uncertainty budget for the calibration of stylus device using DG was prepared. The values of standard deviations of measured depth setting standard and simulated depth profile by DG are similar.

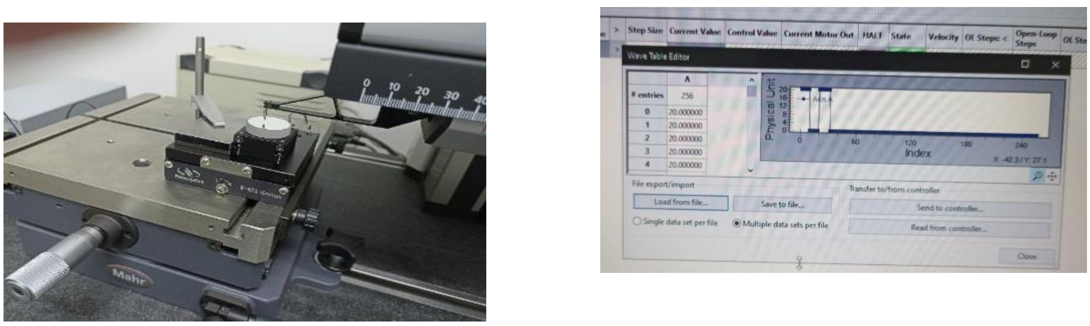


Figure 5. Set up of the DMDM stylus device calibration using DG and simulated depth profile by PiMikroMove software.

IPQ developed a new method for the stylus calibration using an accurate displacement generator (DG) as reference standard. The DG used was a piezo stage with a capacitive sensor design that offers nanometric performance with a resolution of 0.90 nm and a travel of 0-600 µm, allowing sub-nanometre resolution and high linearity with good accuracy. A set up was prepared and assembled to minimise alignment problems (Figure 6).

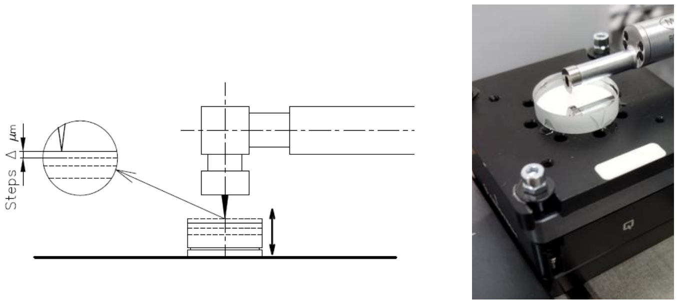


Figure 6. Scheme and image of the measuring system implemented in the laboratory for the calibration of the stylus equipment, where the Aerotech DG is used to generate accurate step/s.

Several stylus calibrations were carried out, using a step with 8.9 µm generated with the available reference standards (gauge blocks, type A depth standard (groove) and the accurate Aerotech DG). A comparison of the measured roughness height parameters, *Ra* and *Rt*, obtained by the scanning in a sample surface, after each stylus calibration, was performed. From the measurement process method used, and from the general principles of the stylus instrument probing process (VDI/VDE 2602-04) several sources of uncertainty were identified and evaluated. In each measured roughness the source of uncertainty in the uncertainty budget that produce differences was the standard uncertainty of the reference standard used in the calibration of stylus instrument. The results were compatible, and from that it was concluded that the use of an accurate DG can improve the measurement uncertainty stated by IPQ in the roughness calibrations. Also, with the DG it is possible to generate accurate and different steps height. This objective was achieved in terms of an uncertainty reduction and capability developed.

In GUM, the calibration of the profilometer using displacement generator was performed in two ways – static and dynamic (Figure 7). For static calibration the roughness measurement device's probe was detached from the drive and mounted separately, while still connected to the device by signal cable. In order to simulate a groove measurement profile under dynamic conditions, the roughness measurement device's probe moved on the gauge block fixed to DG with a constant horizontal speed of Vx = 0,25 mm/s during measurement.

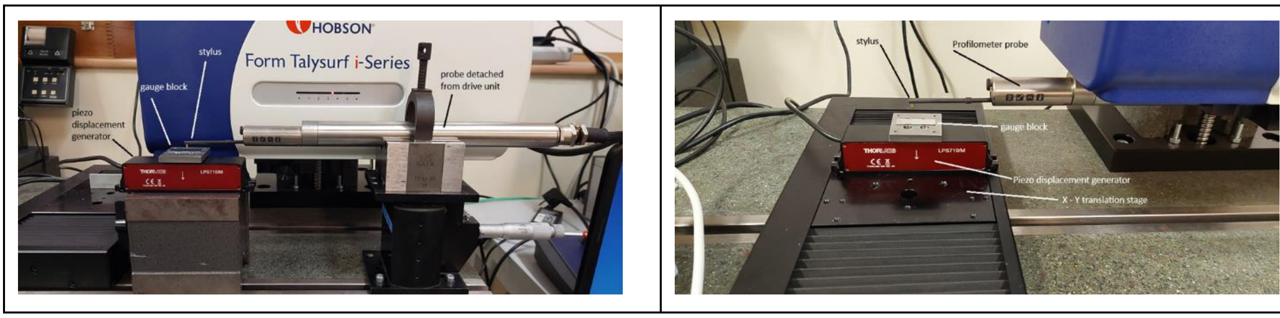


Figure 7. stylus device calibration setup in static and dynamic mode

In both modes, a series of grooves resembling those on GUM primary depth setting standard were generated, ranging from 0,24 µm to 75 µm.

The uncertainty budgets for those calibration routes were prepared, based on budget for calibration with depth standard. However, the differences between DG software reading and measured values were above expanded uncertainty levels for most displacement values. The possible reason for such results was assumed to be the added weight of plate with gauge block mounted on top of the DG, which was close to its maximum load of the DG. This was based on the experience from the calibration of DG itself, with the use of interferometer, where the weight of the optics mounted on the DG had significant influence of the results.

NIS has developed an algorithm called SCS (based on asphere measurements and simplex method for finding fitting parameters of polynomial) for stylus device calibration on a ball standard using Matlab (Figure

8). NIS has also tested it and distributed the calibration coefficients calculated by their software and calculated by Taylor-Hobson software to the partners for an example. In order to show the compatibility between the calibration coefficients calculated by the developed software and the ones calculated by Taylor-Hobson device's commercial software, NIS performed a measurement. This measurement is the example (benchmark).

As an extra work, NIS has started new research for a developed GA (Genetic Algorithms) adaptive algorithm for sphere fitting parameter calculation compared to the existing simplex method with a recursive version (70 % finished). GUM has used the software developed during the project to perform the measurements on the calibration ball. The results were produced and delivered for comparison with other partners. DMDM and IPQ have tested software by data obtained from their own devices.

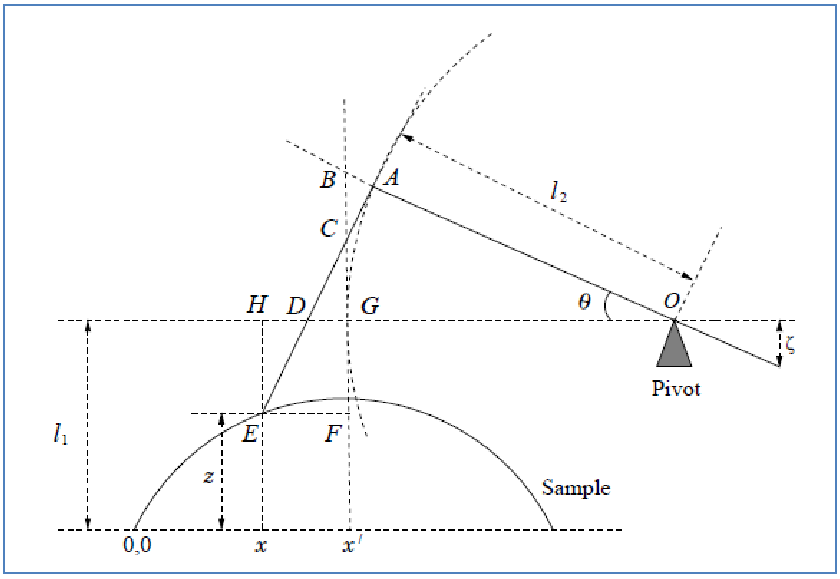


Figure 8. Geometry of arcuate configuration on standard spheric surface

It could be drawn from the results that SCS shows the ability for processing of data acquired from Talysurf system as well as Mahrsurf system. The comparison of radius and form errors obtained by SCS against that by Ultra software shows the reliability of SCS for finding good fitting parameters leading to accepted radius and form errors. The same reliability is expected for the acquired profile by Mahrsurf, however due to some technical difficulties the radius and form errors are not available. But soon, this problem will be solved by cooperation with partners having Mahrsurf.

Key outputs:

- Calibrations of reference stylus instruments using novel portable DGs were achieved with expanded uncertainties (U_{95}) 1 – 70 nm in the setups in the project, except one setup with U_{95} = 300 nm.
- The calibration of the stylus instrument using DG and using groove depth standard are compatible.
- The comparison of radius and form errors obtained by SCS against that by Ultra software (Taylor-Hobson) shows the reliability of SCS for finding good fitting parameters leading to accepted radius and form errors.

4.2 Calibration of reference probes for form measurements in static and dynamic mode using novel portable displacement generators vs existing methods

TUBITAK calibrated the form device probe using a DG (Figure 9) for the whole range D = 0 - 1000 µm depth. DG was positioned in front of the form devices probe horizontally. The form device was also calibrated using only 3 different flick standards and the calibration results were compared with the simulation of flick standard using DG.

Form device probe was calibrated using DG in static and dynamic mode for different upr (undulations per revolution). However, it showed that the first results based on roundness / straightness parameters (ISO 1101) were not compatible with DG's movement. D parameter (ISO 5436) which is used in roughness metrology turned out to be much more compatible with DG's movement. Since D parameter does not exist in form device software, new VBasic codes were developed to calculate D parameter for form device's raw data and to evaluate the results of multiple grooves. The uncertainty budgets for the calibration of form measurement probes using DG have been completed.

Conformity between real calibration using flick standards and simulation of flick calibration produced by DG is proved as following: The deviations of the real measured flicks from the simulation of flicks produced by DGs are much smaller than the uncertainty (Figure 10).

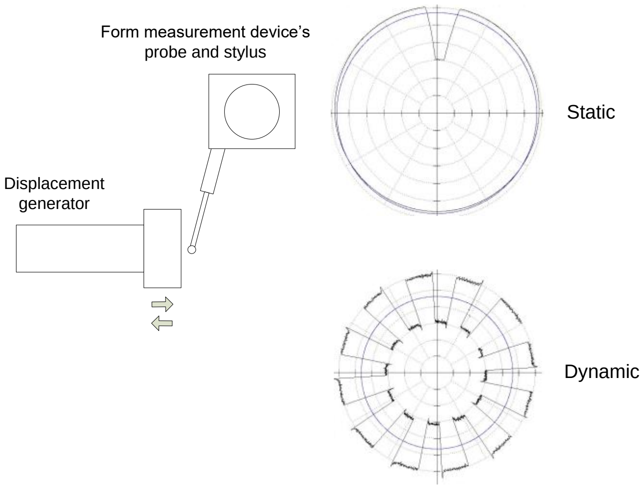


Figure 9. Definition of D parameter for Type A1 (ISO 5436-1) and approximate simulation of flick standard calibration using a DG

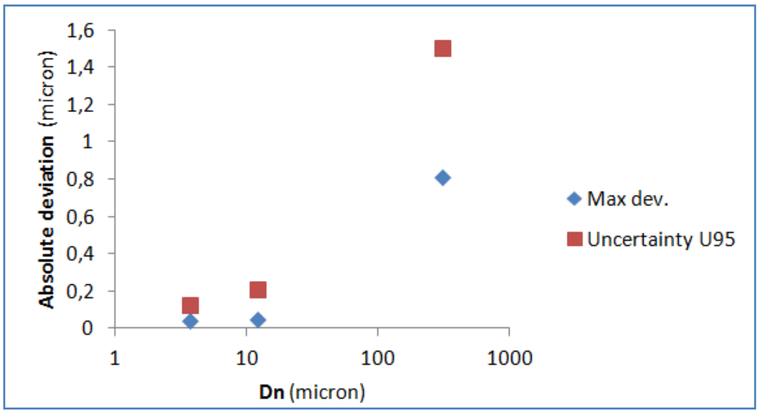


Figure 10. Max deviations occurred and uncertainties of deviations for the comparison

CEM has studied an alternative route for the calibration of form measurement probe. A piezoelectric actuator has been calibrated with a laser interferometric encoder in static and dynamic conditions. The displacement generator has been then used for the calibration of the probe of a high precision roundness measuring machine in both static and dynamic configurations.

Static calibration was performed by generating a 20 µm step and shows a slight discrepancy with respect to the calibration using the current method (flick standard) and has to be studied in future work. The approach employed for the dynamic calibration is to produce a single-frequency sinusoidal wave that is measured by the form device (Figure 11). Frequency analysis can be used to extract the harmonic content and this procedure can be repeated varying frequencies and amplitudes.

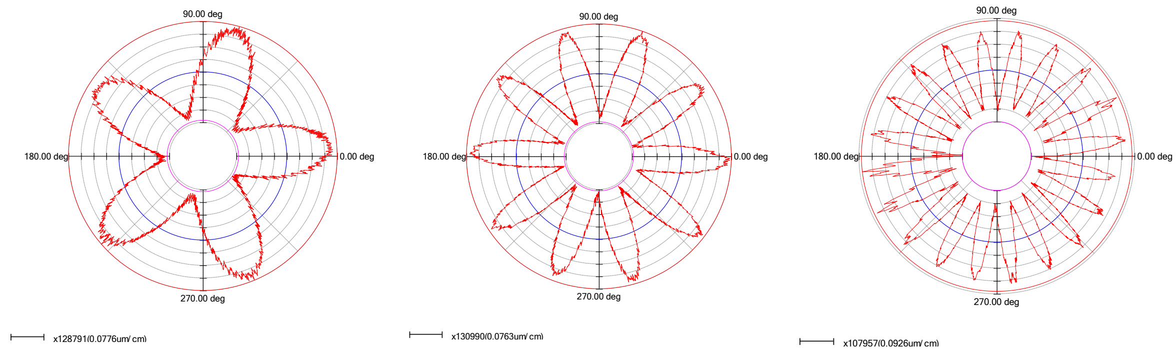


Figure 11: Sinusoidal profiles with 5 UPR, 10 UPR and 20 UPR

The piezoelectric actuator can be used as an alternative to the flick standard and simplifies the traceability to SI, as less steps are needed for the link to the national length standard. The calibration of the piezo relies on a more precise reproducible technique (laser interferometry) and the difficulties associated with the flick standard are avoided (e.g., alignment).

DMDM performed form device calibration with Pi DG in the range up to 7.894 µm (Figure 12). Steps generated by actuator are the same as steps realised by depth setting standards: 0,062 µm 0,236 µm 0,35 µm 0,925 µm 2,61 µm 3,794 µm 7,894 µm. The piezo displacement generator was set under the stylus of the form device in vertical position. For precise and proper measurement, a small optical flat was used at the top measuring face of the DG in order that stylus made correct sense of vertical PG displacement. The movement of the DG is performed by a Pi commercial software PiMikroMove using its Wave Table Editor. Form device probe was calibrated using DG in static mode.

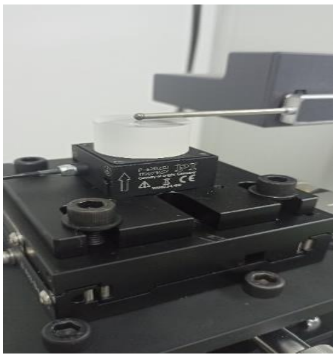


Figure 12 Set up of the DMDM form device calibration using DG

FSB developed a set-up for calibration of roundness measurement probe on MAHR MMQ3 formtester using PI P-621.ZCD stage with servo controller E-625.CR (Figure 13). The special frame for placing DG to the measurement device was made from standard Thorlabs mounting elements. In order to determine the noise level in the system, a static test was conducted (clamping the probe during measurement). The results have shown significant instability, which has been attributed to temperature fluctuations during the measurement.

The implementation of the thermal shield significantly improved the temperature conditions during measurement.

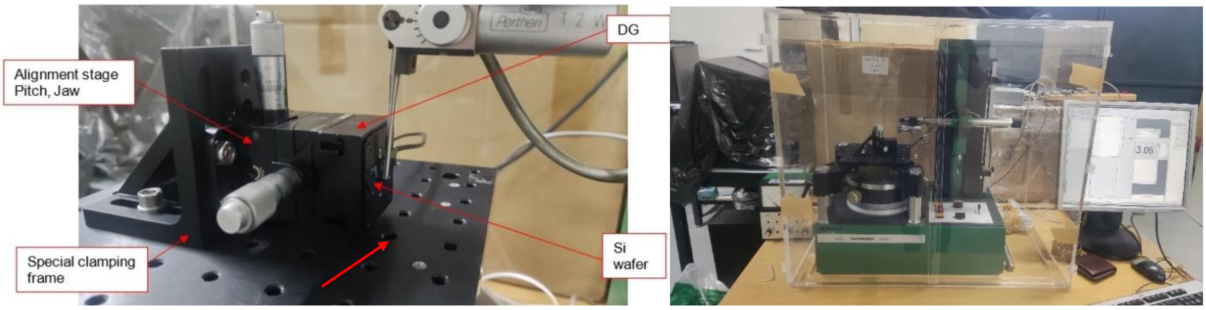


Figure 13. Calibration setup

The research on the misalignment contribution has been conducted, and the measurement uncertainty has been estimated. Comparison of results obtained from the new setup with those from the standard calibration method used in FSB (length machine + interferometer) indicates a significant improvement in terms of measurement uncertainty from 0.040 µm to 0.016 µm.

Key outputs:

- Calibrations of form measuring device's probes using novel portable DGs were achieved with expanded uncertainties (U_{95}) between 10 – 200 nm in the setups.
- The differences between the real flick calibration results and flick simulation results are much smaller than the uncertainty. Therefore, two types of calibration are compatible.
- Because of the limited speed of available DGs, waves with higher upr could not be obtained. Generally highest standard upr value which can be reached is 50 upr in this work.

4.3 Traceable calibration of transducers to be used as portable displacement generators

The transducers or displacement generators (DGs) can be used as a stand-alone device after its calibration by the laser interferometers considering the error sources. It may be possible to reach better uncertainty values than those used together with the laser interferometers. To achieve this, there is a need for further investigations of these items. The detailed investigation on how to use the displacement actuators as portable displacement generators for calibration of roundness and roughness tester probes were carried out considering task specific calibration of displacement actuators in the project.

Considering the requirements for calibration of roundness and surface tester probes, different types of displacement generators (e.g., LPS 65 1" PM LS-072 by PI, LPS710M by Thorlabs, QNP60Z-500 by Aerotech) as a linear positioning system were investigated by the project partners. During the investigations, angular rotational errors (e.g., pitch, yaw) were measured using precise autocollimators and positioning performance of individual displacement actuators was checked by using various displacement interferometers such as (DI-SIOS) by SIOS, XL-80 int. by Renishaw and also by performing an intercomparison measurements between the participants.

To assess the behaviour of the Aerotech DG, an inter-laboratory comparison involved IPQ (pilot), GUM, INRIM, DMDM, CEM and NIS, evaluating the displacements along the vertical axis, by laser interferometry. The reports described the different setups developed and methods used by each participant. Additional measurements to assess DG unwanted rotation (yaw and pitch) when driven at a low frequency up to the full displacement range, were also made and their evaluation demonstrates stability and repeatability. The pitch & yaw results showed a good agreement with the manufacturer specified values. The project demonstrated that DG can be used as portable reference standards to calibrate stylus instruments.

Using the results and knowledge obtained in the project, below information is given for calibration of displacement generators to be used as reference standard for the calibration of stylus instruments and form measurement probes.

The interferometric set-up used by INRIM in the project for calibration of DGS is shown in Figure 14, as example of a double pass differential measuring set-up. Figure 15 shows the interferometric set-up used by TUBITAK in the project for calibration of DGS as example of a single pass differential measuring set-up and a single pass interferometer measuring set-up. Figure 16 shows the interferometric set-up used by GUM. Figure 17 shows the IPQ set-up developed and implemented for the DG calibrations.

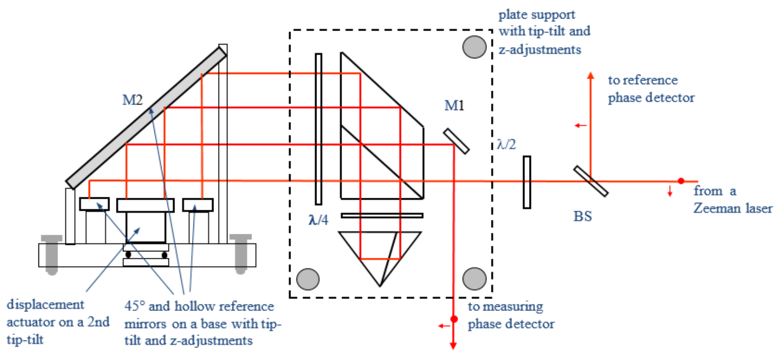
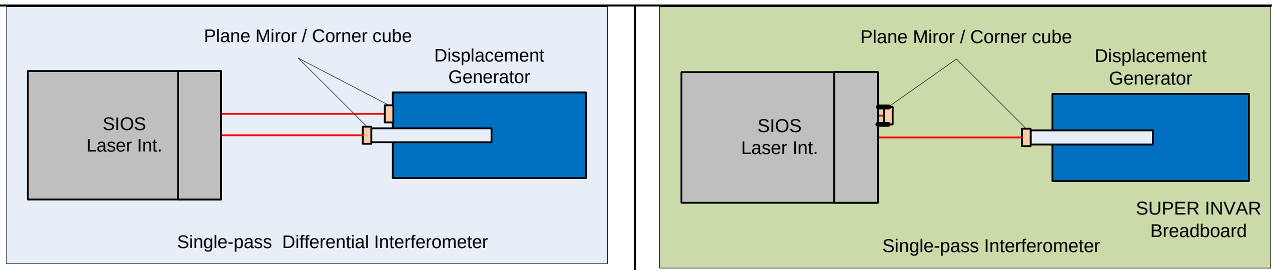


Figure 14. Double-pass differential interferometer used by INRIM



(a) (b)

Figure 15. Single-pass differential interferometer used by TUBITAK (a) differential mode and (b) normal mode with invar plate set-up to reduce thermal drifts

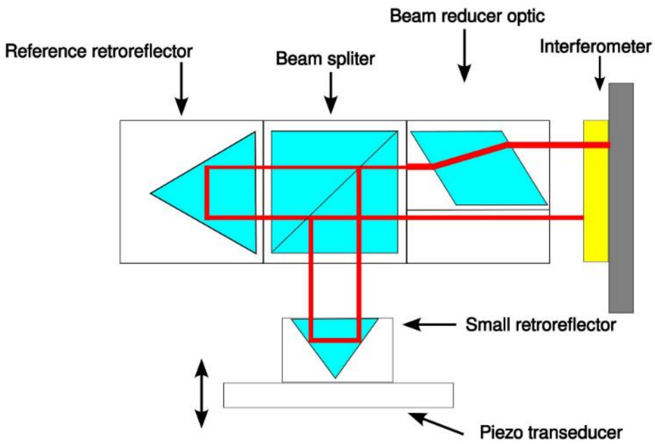


Figure 16. Schematic view of the optical path for the measurements with the XL-80 interferometer system (Renishaw) used by GUM.

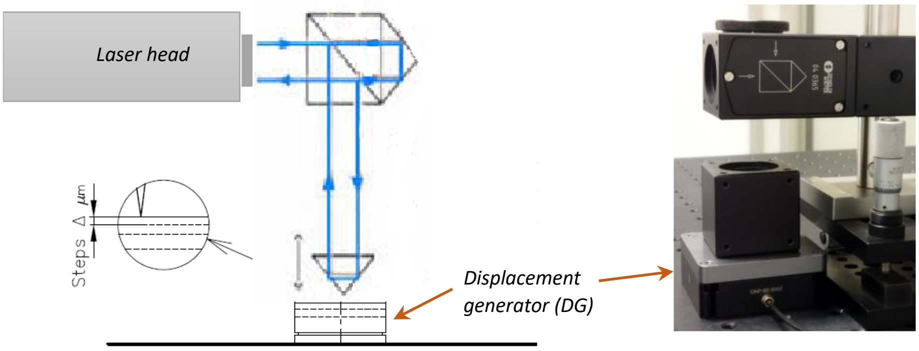


Figure 17. IPQ setup implemented for the DG calibration with a laser interferometer to measure the DG displacement

Figure 18 illustrates the task specific calibration concept used by TUBITAK for calibration of DGs used for calibration of surface stylus and form measuring probes. As stated before, the aim is to calibrate the DG on the conditions used.

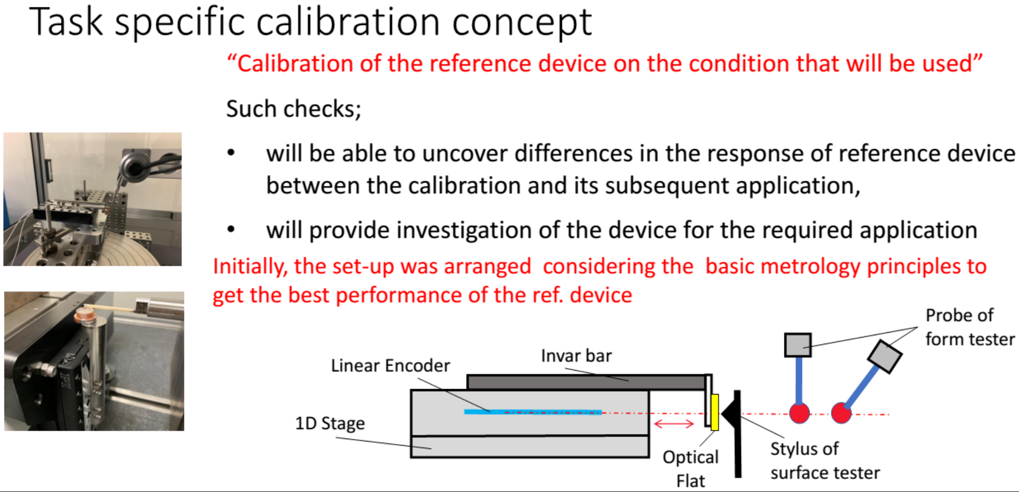


Figure 18. Task specific calibration concept used by TUBITAK for calibration of DGs used for calibration of surface stylus and form measuring probes.

A calibration strategy to uncover the errors in forward and backward directions was selected so that any reversal error (backlash) may be realised. Besides, simple drift check including capability check of the devices in small steps with noise may be done to also check the calibration set-up for any drifts e.g., thermal drifts. This is shown in Figure 19.

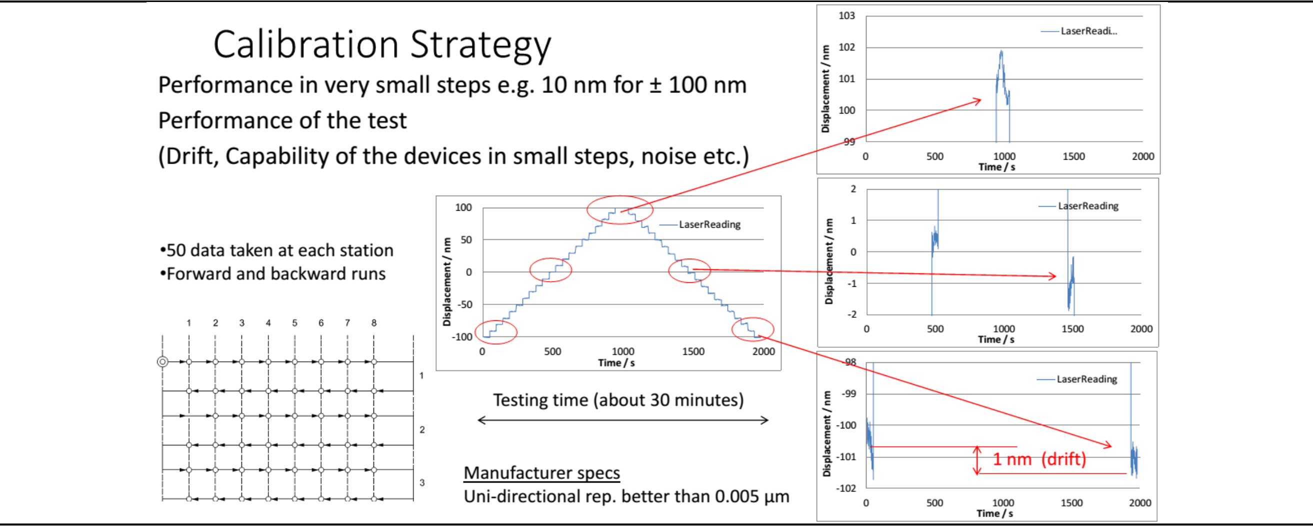


Figure 19. Calibration strategy used in TUBITAK and checking of the set-up

The calibration results for ±1 mm range (in the middle position of the unit) for similar types of DGs are given in Figure 20. The error curves shown in the middle section of the DGs show sudden changes in the error values and direction. This is probably due to changing of pitch error direction causing a displacement error on this region.

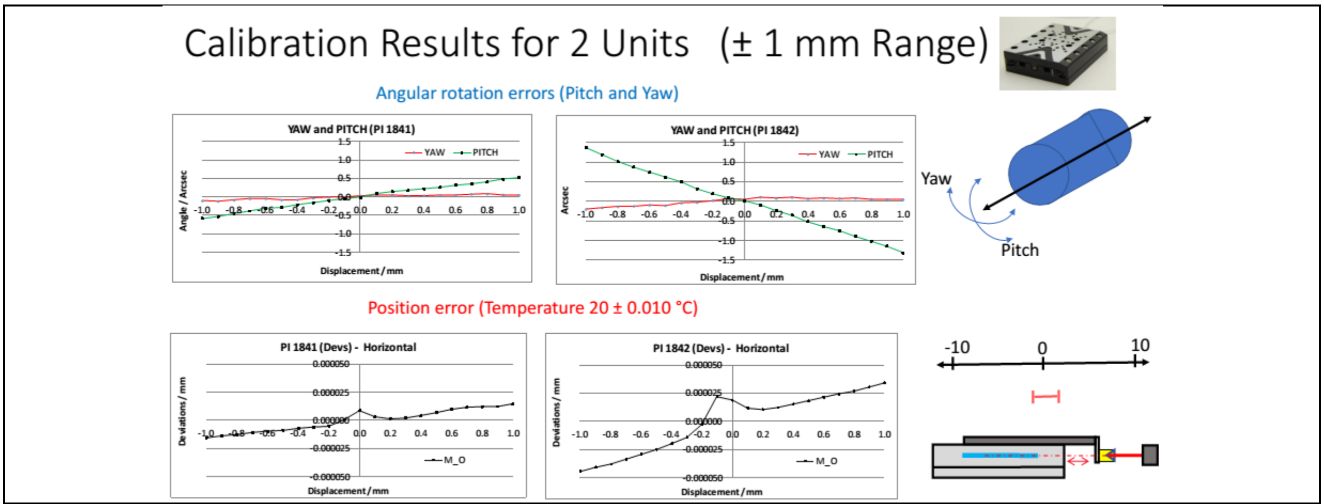


Figure 20. The calibration results for ±1 mm range for similar types of DGs (rotational and displacement errors)

Further investigations were carried out to determine the best section of ±1 mm in the full measurement range of ±10 mm. This is illustrated in Figure 22. Section ranging from -0.2 mm to -2.2 mm shows the best performance having the error of ± 5 nm. Since TUBITAK uses 1 mm range for calibration purposes, 5 nm error is good enough to achieve the required precision. Further tests with the smaller steps in smaller range were carried out to investigate the interpolation errors. This is determined as ± 2 nm as shown in Figure 21.

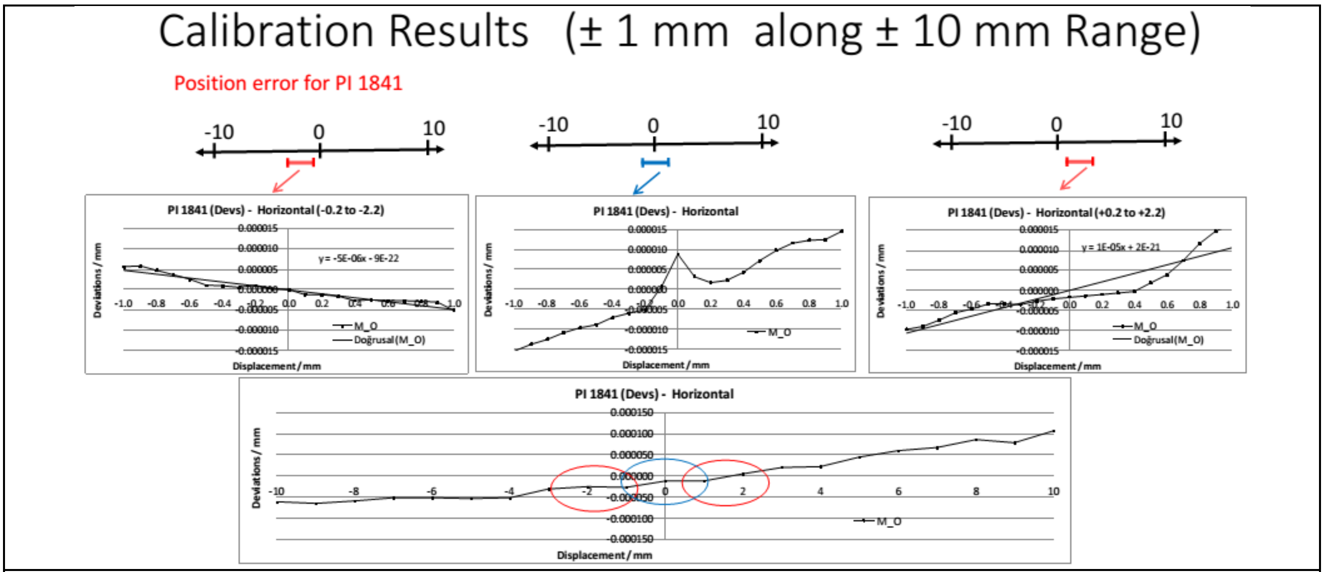


Figure 21. Test results to determine the best section of ±1 mm in the full measurement range of ±10 mm

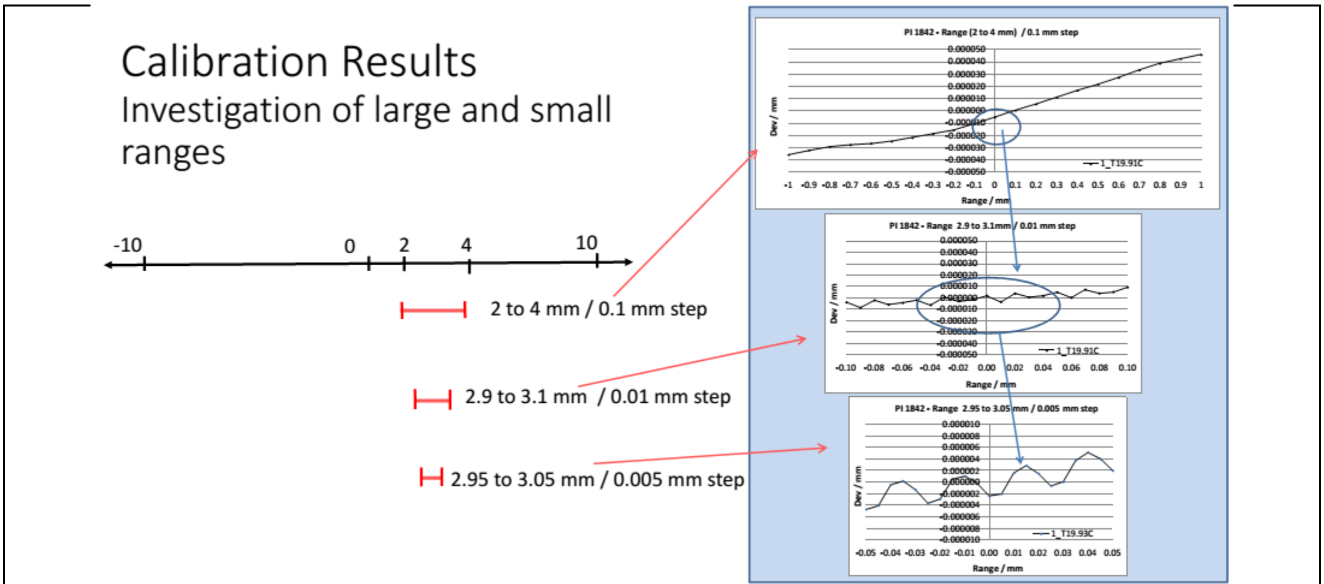


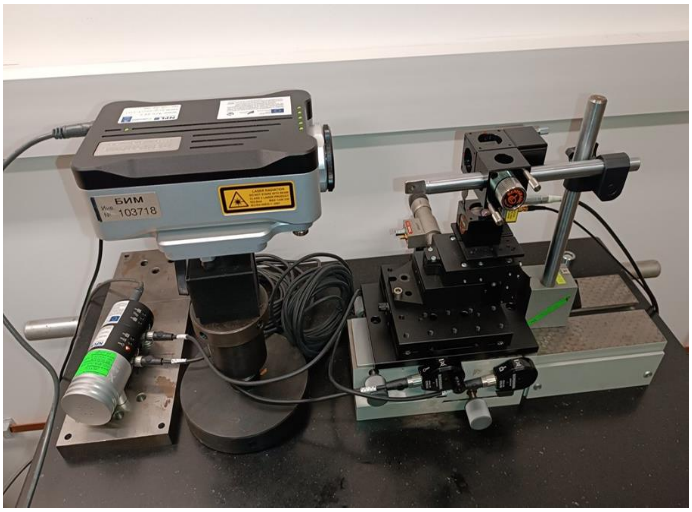
Figure 22. Further tests with the smaller steps in smaller range

The tests performed for static calibration of DGs in TUBITAK can be summarised as given below:

- Displacement generator/actuator (i.e., single axis linear positioning systems) to be used for calibration of surface roughness and form measuring probes was calibrated using a laser interferometer system.
- Metrological traceability was provided, and the performance of the displacement actuator was investigated considering various issues.
- Estimated uncertainty is about U = 5 nm with an error value of 5 nm for 1 mm measurement range to provide traceability.
- It was shown that the displacement generator/actuator under investigation provides a traceable standard for calibration of "reference" surface roughness tester and form measuring devices with uncertainties in the range of 10 nm – 100 nm up to measurement range of 1000 µm.

The dynamic calibration is performed by driving the actuator with different periodic signals and recording the interferometer reading at sufficiently high frequency.

BIM completed and tested the interferometric setup with laser interferometer (Figure 23), Renishaw, XL-80 for calibration of DG. Calibration of DG in whole range has been performed and uncertainty budget has been prepared.



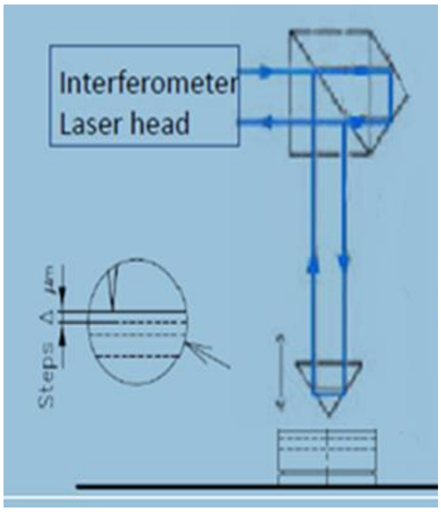


Figure 23. Set up of calibration of the DG with laser interferometer, Renishaw, XL-80.

DMDM completed and tested the interferometric setup with laser interferometer (Figure 24), Renishaw, XL-80 for calibration of DG. Calibration of DG in whole range has been performed and uncertainty budget has been prepared.

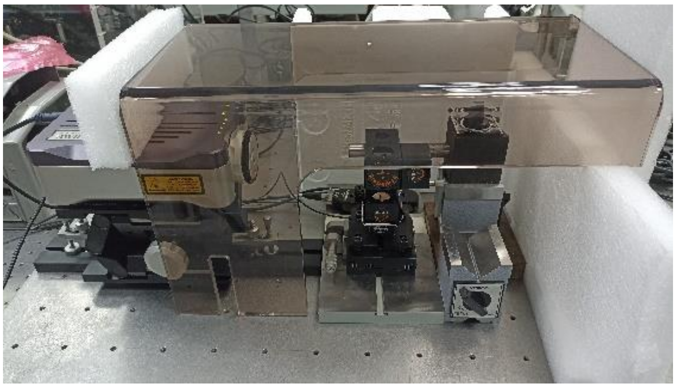


Figure 24. Set up of calibration of the DG with laser interferometer, Renishaw, XL-80.

The displacement actuators in GUM were driven to simulate grooves of the required depth repeatedly using a square excitation. Resulting signal recorded is shown in Figures 26 and 27 with the example of ringing oscillations observed in the simulated groove of 75 µm.

At GUM with Thorlabs piezo actuator LPS710M to mitigate the influence of such oscillations on the results, changes in the actuator position were held for at least 10 folds the settling time of the actuator. The settling time was expressed as the time elapsed from the moment the actuator reached 2 % of the required groove's depth to the moment from which oscillations around the target position were lower than 2 % of the required depth. The settling time was approximately 75–80 ms, regardless of the target depth. After adding some additional margin, it was decided to generate the grooves to be a minimum of 1 s wide.

These are the recommendations for the dynamic calibration when the displacement actuators were driven using a square excitation:

- Arrange the PID parameters of the control system to minimise the overshoot problem (or ringing oscillations) (if needed get help from the manufacturer).
- If the overshoot or ringing oscillations problem still exists, obtain the raw data and evaluate according to the ISO 5436-1:2000.

If the problem still exists, then raw data obtained may be filtered for these data sets. Figure 1 illustrates the schematic view for calculation of the groove's depth according to the ISO 5436-1:2000 which is used for mitigation of the ringing oscillations / overshoot problem during calibration of the contact probes. Detailed information can be taken from REF 1 and REF 2.

The use of DGs to perform a dynamic calibration of tactile probes was proposed by INRIM in order to simulate the contact with artefacts of various forms and check the dynamic performance of roundness and surface tester probes. A soft-tool was implemented with the aim of generating a signal as the sum of 10 frequency components without reverberation. A csv file was created and uploaded into the driver of INRIM z-stage actuator, model PI P620-ZCD. Then, the tactile stylus probe was placed in contact with the z-stage actuator and a comparison between the driving signal, the position monitor of the z-stage and the probe signal has been performed. A schematic representation of the set-up is shown in Figure 25.a).

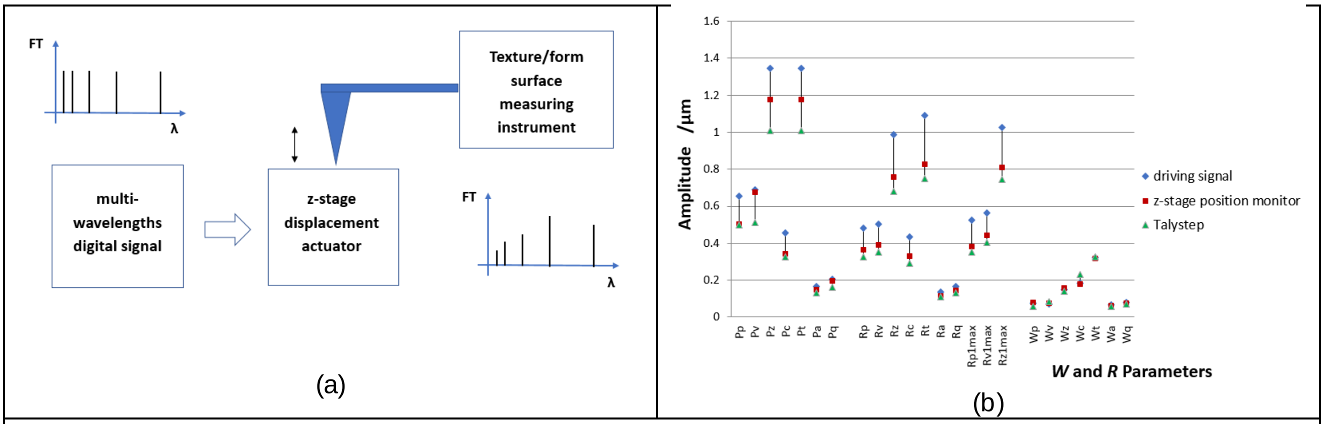


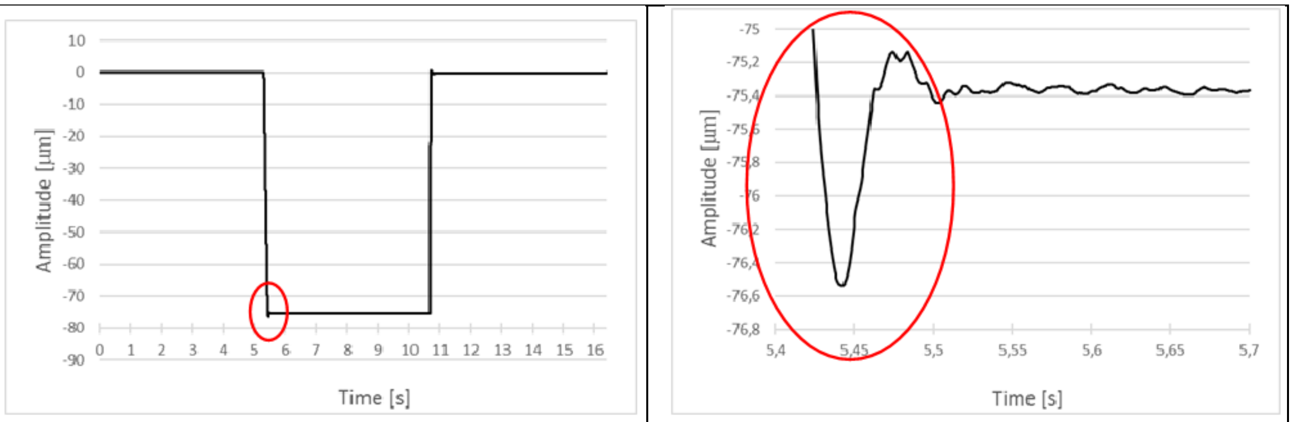
Figure 25.a Experimental model for the dynamic calibration of tactile probes with DGs driven by complicated signals; 25.b signal analysis performed by means of Mountains Map software in terms of W and R parameters

Non negligible differences in terms of bandwidth and noise were observed in the spectrum analysis of three recorded signals. Figure 25.b shows the analysis performed by means of Mountains Map software in terms of W and R parameters: amplitude changes up to 20 % of the peak parameters (Rz, Rv, …) calculated from the different signals that are visible. The amplitude reduction is less noticeable with the average parameters *Ra, Rq* and with the waviness parameters *W.*

Good practice guides were drafted using the above information. In summary, investigations show that linearity, hysteresis between outgoing & ingoing paths, repeatability, and stability on time are essential for use of the displacement generators. The performance of displacement generators needs to be checked for unwanted rotations, such as pitch and yaw motions, over the entire range, in different orientations (vertical/horizontal), and at different speeds. The precautions for calibration of displacement generators may be considered as; (i) minimising the Abbe offset between the axis of the actuators and the interferometer (later for the probe / stylus axis), gauge temperature, ambient parameters (temperature influences may be reduced using low CTE materials and smart set-ups), (ii) avoiding mechanical constraints on displacement generators during assembling and arrangement of the cables and finally, (iii) reducing interpolation errors of the interferometer varying mostly in the range of (1–5) nm with smart strategies.

Similarly, almost all partners calibrated their DGs using various interferometric set-ups. According to output of all this work, the main parameters that influence the calibration of displacement actuators and represent the main sources of uncertainty are listed below:

- interferometer readings
- laser wavelength
- index of refraction
- optics non-linearity
- thermomechanical stability
- uncompensated thermal expansion
- dead-path error
- optics thermal drift
- Abbé error
- cosine error
- polynomial regression
- repeatability



(a) (b)

Figure 26. Resulting signal recorded using a square excitation in GUM (a) Example of ringing oscillations observed in the simulated groove of 75 µm (b) Zoomed-in oscillations at the falling edge of the groove [REF 1 and 2]

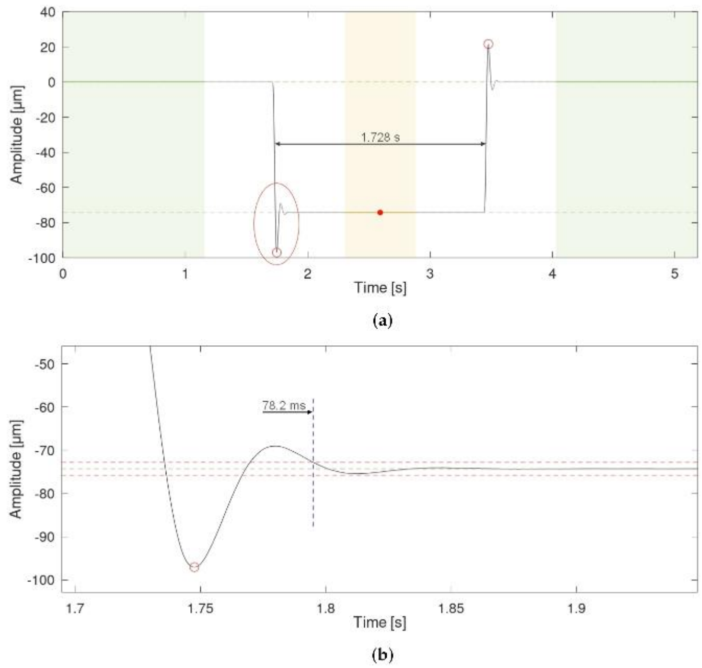


Figure 27. Example of ringing oscillations observed in the simulated groove of 75 µm. (**a**) The green dashed lines represent the model fitted according to ISO 5436-1:2000 standard. These lines are extrapolated along the time axis for visual guidance. The red ellipse indicates the zoomed-in area shown below. Small red circles indicate peaks of the oscillations: 22.8 µm for the falling edge and 21.9 µm for the rising edge respectively. Green-shaded areas are placed over external measurement lengths and the orange-shaded area is placed over the central measurement length. The red dot indicates the middle of the central length; (**b**) Zoomed-in oscillations at the falling edge of the groove. Red horizontal lines represent 2 % deviation from the target depth. The blue vertical line represents the end of the settling time. The settling time equals 78.2 ms.

REF 1: Trych-Wildner A, Wildner K, Sosinowski P2022 Feasibility Study of a Piezo Actuator as a Potential Standard in Calibration for Roundness Instruments, Sensors 22 9312

REF 2: Yandayan et al, Traceability issues for contact probe and stylus instrument measurements, Euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023.

Key outputs:

- Investigations were performed for use of DGs as reference standards for calibration of surface roughness devices and for form measuring probes. The aim was to establish direct traceability link to SI unit metre via the laser interferometers with the uncertainties of 5-10 nm using the recently developed piezo stages. Further advantage is to calibrate these devices for dynamic response as well as static response.
- Different types of DGs with different manufacturers were investigated using various state of the art set ups realised by various laser interferometers. The performance of the stages/actuators was tested in various orientations (vertical/horizontal) aiming to achieve task specific calibration. Further work was done by investigating the angular rotational errors using precise autocollimators to determine the uncertainty components (e.g., due to Abbe errors).
- Evaluation of the data sets was performed using various approaches and comparison of the results was performed with the regular standards calibrated by advanced NMIs. Excellent agreement was realised.
- It was concluded that DGs are good candidate to calibrate both surface roughness styluses and form measuring probes in both dynamic and static mode promising to replace the current standards with a very cost-effective way particularly in terms of reduced uncertainty and achieving direct traceability to SI unit metre.

4.4 Development of noise reduction software

A VBasic software for random noise reduction in surface roughness and form profiles was developed based on the method of H. Haitjema and M. A. A. Morel ("Noise bias removal in profile measurements," Precision Engineering Section, Eindhoven University of Technology, vol. 38, no. 1, pp. 21-29, 2004). Any type of profile measurements is repeated several times under exactly the same conditions. According to the method, random noise reduction performed in 2 different ways:

Method1: Reduction of Fourier components. Fourier components of the repeated measurement profiles were calculated using DFT (Discrete Fourier transform). All Fourier components which were determined to be random according to a special criterion, are taken as completely zero. Then the object profile is reconstructed using IDFT (Inverse Discrete Fourier Transform).

Method2: Random component exclusion. Starting from the Fourier components with minimum randomness, Fourier components are added to Fourier Synthesis (IDFT). When R_q^2 parameter (root mean square roughness) of reconstructed profile reaches a special targeted R_q^2 value, the adding process is stopped.

In Figure 29, roughness measurements of a surface (sine wave) with highly random noise and the profile obtained by simple averaging and the profiles generated by NBR are presented. It can be seen how Method1 and especially Method2 eliminate random roughness better than simple averaging of repeated measurement profiles.

In addition to TUBITAK's development of a stand-alone application for NR in roughness and roundness measurements, FSB has created Python code for NR of roundness data (Figure 28). This code incorporates functions that support the Averaging method, Reduction of Fourier components, and Exclusion of Random components. The Python NR module can be effortlessly imported into any Python project, making the NR functions accessible. In this way, NMIs and stakeholders can develop their own software for roundness analysis and utilise the pre-developed NR functions from this project. Using optimised routines from the NumPy library decreased the computation time. Testing has demonstrated that 12 roundness traces, each comprising 10,000 data points, can be processed within 10 seconds, irrespective of the chosen NR method.

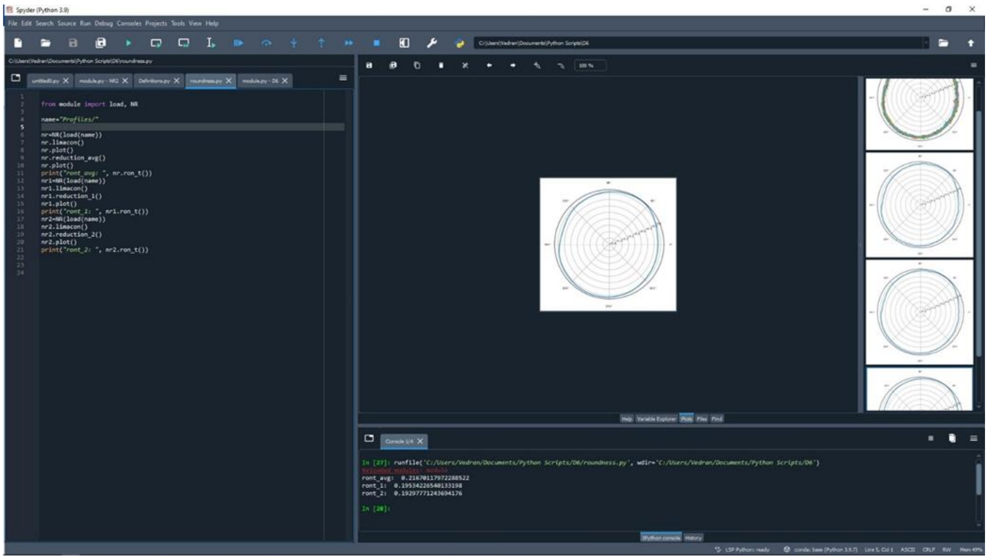


Figure 28. Example of measurement script with calculated results in Spyder environment (opensource)

The software evaluation was made in two ways: through a result obtained from the original code developed by the author of noise reduction methods and using generated soft data. The comparison results showed good agreement between the *RONt* and *RONq* parameters. The results obtained from the generated test data demonstrated a significant reduction in noise level. Both, *RONt* and *RONq* parameters approached their theoretical values when noise was not added to the generated profile. Noise reduction was successfully applied to the actual roundness measurement results provided by FSB, TUBITAK, GUM, and CEM while IPQ and DMDM couldn't access the raw data necessary to obtain noise reduction on their roundness measurement equipment.

The NBR and NR software were tested by all project partners using both simulated and real profile measurement data. Last version of the software was uploaded to Zenodo repository as open access.

Noise reduction for random noise is not used in commercial devices and becomes important for measurements carried out in noisy industrial environments. In roughness measuring devices gaussian short wavelength filter is used as standard method to eliminate mechanical and electrical background noise. This filter works as a "lowpass" filter. The filter eliminates surface components whose wavelengths are shorter than a specified cut off wavelength. So, if the wavelength of the random noise is larger than the wavelength of the filter, random noise cannot be eliminated. Whereas, in the NBR method, the roughness measurements are repeated several times under exactly the same conditions, and the surface components that are determined to be of random character, are eliminated regardless of wavelength. Therefore, the decrease in roughness parameters caused by NBR method will be larger than the decrease in roughness parameters caused by short wavelength filter. This can be shown for P_q parameter of roughness measurements in Figure 30 (P_q: Root mean square of surface deviations in primer profile).

1	j	1.MEAS	2.MEAS	3.MEAS	4.MEAS	5.MEAS	MEAN	1.MTD	2.MTD
2	0	33,8903	30,7567	23,2019	19,407	14,4751	9,60403	4,80265	0,00181
3	1	35,8637	29,805	25,4318	20,7007	13,8026	10,3786	5,33371	0,00803
4	2	33,6204	30,0499	23,1572	20,5727	14,2235	9,58255	4,90874	0,01426
5	3	33,7329	29,5591	24,1487	20,1108	16,1636	10,0009	4,86199	0,02048
6	4	34,4104	29,4628	25,8338	20,197	14,8976	10,2181	4,86353	0,0267
7	5	35,2453	28,3711	24,7124	20,7493	13,946	9,86264	4,81892	0,03292
8	6	33,8013	30,4508	25,9381	20,3231	13,7128	10,103	5,18483	0,03914
9	7	33,3646	29,2104	24,09	19,3231	16,0891	9,67327	5,20116	0,04536
10	8	33,1438	29,0982	23,3106	19,3215	15,0933	9,25133	4,58249	0,05158
11	9	35,3113	28,848	23,5326	19,2436	14,5937	9,56369	4,92333	0,05779
12	10	33,9563	29,0215	23,8774	20,3885	15,2166	9,74987	4,87641	0,06401
13	11	32,992	28,6453	24,2238	18,6332	14,3887	9,03443	4,55741	0,07022
14	12	35,1363	28,5039	24,2054	21,0236	15,9129	10,2142	5,00162	0,07642
15	13	33,8618	29,651	24,1104	19,3919	14,1315	9,48714	4,76606	0,08263
16	14	34,8729	30,7038	25,5087	20,3319	14,7648	10,4942	5,3356	0,08883
17	15	35,6898	30,4758	25,3869	18,7898	13,4106	10,0084	5,23446	0,09502
18	16	35,8507	30,5312	24,6959	18,7445	14,9988	10,222	5,14246	0,10122
19	17	33,4455	29,163	23,8503	20,8075	14,5694	9,62495	4,56126	0,10741
20	18	35,0915	28,5361	23,806	18,5003	15,5149	9,54758	4,72727	0,11359
21	19	33,2743	31,0239	24,0946	21,1891	15,1195	10,1981	5,24927	0,11977
22	20	34,5261	29,9019	24,9235	18,9833	14,1449	9,75375	4,97936	0,12595
23	21	34,2825	29,1567	23,265	19,9311	14,4631	9,4775	4,77819	0,13212
24	22	34,1399	29,3881	23,4183	19,7593	15,9869	9,79633	4,9532	0,13829
25	23	35,5995	30,1182	23,8377	19,6716	14,3928	9,98178	5,18295	0,14445
26	24	33,2875	28,8168	25,1032	20,9058	15,4058	9,96164	5,05885	0,1506
27	25	33,9355	29,9662	25,6477	20,2022	14,5864	10,1254	5,12621	0,15675
28	26	33,5176	29,4447	23,6535	19,9776	14,0474	9,38599	4,97479	0,16289
29	27	34,6046	29,6414	26,1296	20,0689	14,0681	10,1604	5,00237	0,16903
30	28	34,0049	29,3161	25,3821	20,7044	14,9563	10,1306	5,25495	0,17516
31	29	33,7317	29,409	25,4937	18,9815	15,3524	9,85147	4,77759	0,18128
32	30	35,4301	29,4406	26,2133	21,2611	14,6441	10,6556	5,63652	0,1874
33	31	35,1106	29,8264	25,303	18,5009	13,74	9,75402	5,02785	0,19351
34	32	35,903	29,388	23,4498	19,7071	15,7004	10,0875	5,15627	0,19961
35	33	33,9349	28,4579	24,6724	19,2222	14,9859	9,51249	4,93892	0,2057
36	34	33,2731	29,645	25,677	20,9372	14,2901	10,0223	5,12455	0,21178
37	35	35,3672	29,3038	25,0568	19,4224	14,3064	9,94915	5,09312	0,21786
38	36	33,9199	28,8282	24,8969	21,2371	13,6314	9,76054	5,07758	0,22393
39	37	35,6675	28,6631	25,3488	20,8922	14,4451	10,2612	5,27914	0,22999
40	38	35,8676	28,5952	24,7367	19,2896	16,2983	10,2153	5,08645	0,23604
41	39	35,3495	28,8986	25,7529	18,4199	14,2662	9,79523	4,76076	0,24208
42	40	35,8175	29,8495	24,325	19,2221	14,9406	10,0888	5,05874	0,24811
43	41	34,5819	30,3234	23,6561	19,1461	14,0935	9,61801	4,98911	0,25413
44	42	35,4433	28,5817	26,1806	19,0423	13,7659	9,86059	5,10931	0,26014
45	43	33,8054	30,1767	24,4634	18,7587	15,7653	9,85172	5,29744	0,26614
46	44	35,04	29,4412	26,2057	20,5535	14,8769	10,4813	5,53501	0,27213
47	45	33,2828	28,4087	25,1168	21,2466	14,1217	9,69311	5,03321	0,27811
48	46	33,3737	29,8823	25,6285	19,5943	15,3084	10,0153	5,092	0,28408
49	47	35,0519	28,7423	24,7669	18,6798	16,3945	9,98489	5,03335	0,29004
50	48	35,3235	30,4782	24,49	20,1962	16,3562	10,6266	5,28618	0,29598
51	49	33,4989	30,2317	24,8151	19,2369	15,7191	9,95814	5,078	0,30192

ProfileName: Y = 0x + 0 + 1Sin(1x + 0) + 0Cos(0x + 0) + 3(Rnd(1) - 0.5)

	1.Meas	2.Meas	3.Meas	4.Meas	5.Meas	Mean	1.Method	2.Method	Lc	n	Ln
Rt	4,914	4,955	4,836	4,879	4,886	3,661	3,163	1,981	-	-	-
Ra	0,900	0,950	0,933	0,899	0,887	0,677	0,645	0,631			
Rz	3,259	3,223	3,267	3,172	3,247	1,950	1,364	0,469			
Rmax	3,662	3,451	3,664	3,475	3,531	2,409	1,713	0,855			
Rq	1,099	1,149	1,138	1,095	1,081	0,798	0,740	0,700			

* Roughness parameters are approximately defined/calculated

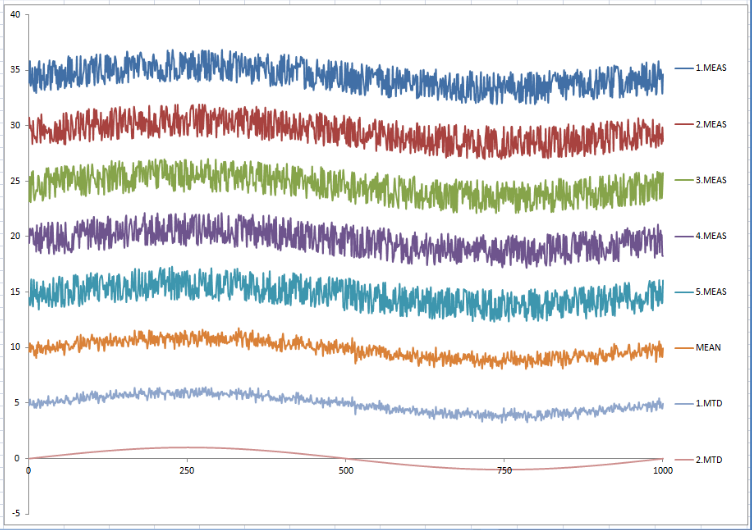


Figure 29. Roughness measurements of a surface (sine wave) with highly random noise and the profile data generated by NBR. (Upper 5 profiles are repeated measurements, the 6th profile from top is simple averaging, the 7th profile belongs to NBR Method1 and the 8th profile belongs to NBR Method2)

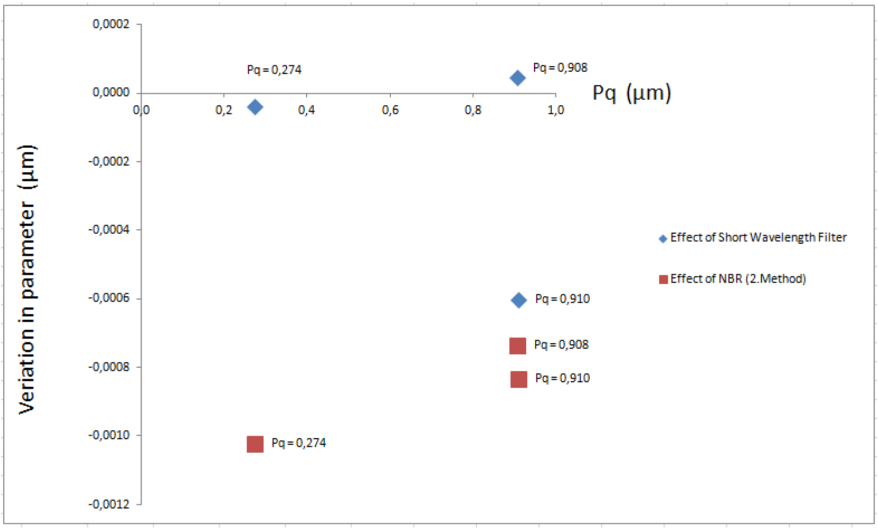


Figure 30. Comparison of the effect of short wavelength filter and the effect of NBR (Method 2) on Pq parameter of the real roughness measurements

- NBR method can be used to eliminate random noise both in roughness and roundness measurement profiles. Noise's amplitude can be eliminated by 95 %.
- Generally the decrease in roughness parameters caused by NBR method is more than the decrease in roughness parameters caused by short wavelength filter. It is presumed that this is because surface components with wavelengths longer than the cut off wavelength of the short wavelength filter are randomly generated during repetitions and are not eliminated by short wavelength filter. But in the NBR method, all surface components that occur randomly during measurement repetitions are eliminated regardless of their wavelengths.

5 Impact

The webpage developed, www.probetrace.com, is regularly updated with news and information such as project reports, articles/papers published by the partners and details of project meetings.

The national dissemination of ProbeTrace activities in 2022 and 2023 continued with publications of articles in the IPQ newsletter. Two articles were presented in ESPAÇOQ no. 191 and no. 198.

IPQ disseminated information on the project by giving poster or oral presentations at: 23rd National Physics Conference FISICA2022 (https://fisica2022.sci-meet.net/) Faculty of Sciences of the University of Porto, Portugal, September 2022; IMEKO TC11 & TC24 Joint Hybrid Conference, October 17-19, 2022, Dubrovnik, Croatia; 8th SPMET National Meeting (http://www.spmet.pt/encontro8.html) in November 2022; 21st International Metrology Congress, Lion, France, March 2023 and the Workshop for traceability of contact probe and stylus instrument measurements in Belgrade (Serbia) in May 2023.

TUBITAK disseminated information on the project by giving poster at (Measurement Science Symposium and Exhibition in Turkey (https://zenodo.org/record/4467505#.YBK1ATEzapo) in November 2019; euspen's 23rd International Conference & Exhibition, Copenhagen, DK, June 2023 and 21th International Metrology Congress CIM 2023, Lyon, France, March 2023.

BIM has participated in the 30th International Scientific Symposium Metrology and Metrology Assurance 2020, held in Bulgaria and presented a paper on the project's purpose (http://metrology-bg.org/fulltextpapers/Proceedings_MMO_2020.pdf).

FSB has published an article in national trade magazine Svijet po mjeri (2020). An oral presentation was given at the 16th International conference CROLAB 2021, in Croatia in October 2021. FSB has published newsletter "Workshop on Novel methods for traceability in Form and Surface Roughness Measurements" posted on the website www.fsb.hr. FSB has disseminated project work related to the noise reduction of roundness data on international conference IMEKO TC11 & TC24 Joint Hybrid Conference, October 17-19, 2022, Dubrovnik, Croatia.

CEM introduced the ProbeTrace project on their institutional website, and also published a popular press article in the *e-medida* magazine in July 2023 "Trazabilidad en medidas de rugosidad y redondez: proyecto europeo ProbeTrace – Revista e-medida", presenting some of the work done during the project to large audience in Spain and other Spanish-speaking countries.

GUM introduced the ProbeTrace project on their institutional website.

Impact on industrial and other user communities

The participant NMIs have established new services for calibration of form and surface roughness standards using the traceability route established with the novel methods developed in the project. They started calibrating their reference form measuring devices and stylus instruments. Improvements for calibration of form and surface finish standards through investigations of contact measurement probes and stylus instruments enable NMIs to calibrate their own devices by themselves without having to use calibrated reference standards of advanced NMIs. This also provides traceable and more reliable measurements of form and surface finish parameters to various industries (such as automotive, aerospace and energy) in the participant countries as well as in Europe. In addition, newly developed guides will facilitate the application of the new methods for CMM, form and stylus instrument users and manufacturers. The project outcomes also offer solutions for the improvement of measurements taken in noisy industrial environments by applying developed noise reduction software tools.

Impact on the metrology and scientific communities

Newly developed methods, which provided alternatives to the conventional ones, are creating impact on calibration laboratories. The outputs of the project results were presented to emerging NMIs, accredited labs, end users and manufacturers in the joined capacity building workshops arranged together with EURAMET Capacity Building Officer and EMN for Advanced Manufacturing. Knowledge transfer from experienced NMIs to those less experienced on how to use these new types of standards proved to be very beneficial. On a broader scope, the project has strengthen the collaboration of European NMIs and has increased their competitiveness and consistency by producing a draft calibration guide for the use of portable DGs for calibration of stylus instruments and contact measurement probes. At the end of the project, the results showed that the project has provided valuable information to extend traceability of most probing-based form and surface texture measurements at the emerging NMIs.

Impact on relevant standards

A presentation about the project results and an input for testing of the dynamic performance of stylus instruments "Areal and profile surface texture" were given at ISO/TC 213/WG 16 N 1177 meeting. The consortium has also promoted the results of the project within other committees, e.g., EURAMET TC-L, COOMET TC Length and Angle, IMEKO TC 14 Geometrical Quantities. The process of drafting EURAMET guides for calibration of stylus instruments and form measuring probes was initiated in the last meeting of EURAMET TC-L using the information produced in the good practice guides. It is expected that, beyond the project, there will be a contribution to a further revision of ISO 12179 - Use of depth setting standards for calibration of contact stylus instruments. The project results were also presented to GULFMET and AFRIMET.

Longer-term economic, social and environmental impacts

Measurement of form and surface finish parameters relate to functionality of manufactured parts. Better achievements for the desired tolerances on automotive parts will provide better engine parts working more efficiently with improved fuel savings, longer lifetime, reduction in waste and production time, which altogether will have a positive impact on the environment.

Manufacturers in advanced countries of Europe (such as Germany and France) are establishing manufacturing plants in other countries of Europe and also in Asia, Middle East and Africa. In order to sustain similar quality of the manufactured parts, there is a need for development of metrology capabilities in the respective countries. The project has already started providing this (e.g., some EU NMIs asked to use output of the project) for surface roughness and form measurements, which will in turn result in improvements of manufacturing processes. This will increase economic growth in Europe and its neighbouring region(s) and enhance industry competitiveness and will therefore be instrumental for creating jobs particularly in the production of parts in a cost-effective way.

6 List of publications

Baršić, G., Šimunović, V. (2021) '18PRT01 Probe Trace Traceability for contact probe and stylus instrument measurements', *6th INTERNATIONAL CONFERENCE, LABORATORY COMPETENCE 2021*, p. 70-75. Available at https://zenodo.org/record/7092497

Saraiva, Fernanda et al (2023) 'A novel traceability route to the SI in roughness measurements at IPQ', *Acta IMEKO*, 12(3) p. 1-5. Available at https://doi.org/10.21014/actaimeko.v12i3.1456

Wildner, K., Trych-Wildner, A., Sosinowski, P. (2022) 'Feasibility Study of a Piezo Actuator as a Potential Standard in Calibration for Roundness Instruments', *Sensors*, 22 p. 9312. Available at https://doi.org/10.3390/s22239312

Šimunović, V., Baršić, G. (2024) 'Evaluating the spindle error of the roundness measurement device', *Measurement: Sensors*, 32 101038. Available at https://doi.org/10.1016/j.measen.2024.101038

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/